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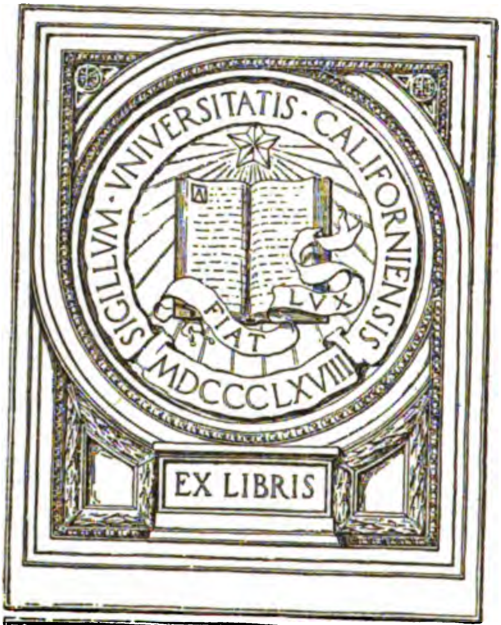
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AMERICAN
HYDROELECTRIC PRACTICE

A COMPILATION OF USEFUL DATA AND INFORMATION ON THE DESIGN, CONSTRUCTION AND OPERATION OF HYDROELECTRIC SYSTEMS FROM THE PENSTOCKS TO DISTRIBUTION LINES

BY

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ENGINEERING (U. S. A.)

FIRST EDITION

UNIV. OF
CALIFORNIA

McGRAW-HILL BOOK COMPANY, INC.
239 WEST 39TH STREET. NEW YORK

LONDON: HILL PUBLISHING CO., LTD.
6 & 8 BOUVERIE ST., E. C.
1917

TK 1001
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PREFACE

No attempt has been made to make this work a text-book on design in the sense that it should give the fundamentals on which the design and construction of parts of a hydroelectric system are based. It is, on the other hand, a compilation of the practical and essential features of design, construction and operation as worked out in many plants and systems, interpreted and arranged for convenient use and reference by plant designers, constructors and operating engineers. Unlike the usual handbook, it explains how certain results have been obtained under particular conditions and deals with the unusual as well as the general run of conditions in both construction and operation. To carry out the aim of the text, therefore, the authors have drawn liberally on published experiences and solutions of system problems and those features of plant layout essential to the subject matter treated. When the text is critically analyzed, apparent gaps may appear. For instance, the design and construction of dams and complicated station and large substation structures have been omitted. This has seemed advisable since these are specialized fields of engineering calling for particular and individual consideration by a specialist who need not be essentially an electrical engineer or operator and therefore outside the scope of this work. Likewise specifications for apparatus and details of equipment have been given only briefly, for the reason that the engineer who will find this book of value will be in possession of this information and will find the information recorded of greatest use as a guide in formulating, arranging and comparing plans and specifications, operating results and the like, with the actual results worked out in particular cases. The material in Chapters I, II, III and VI has been largely supplied by Mr. Taylor, interpreted and supplemented from his own experience in plant work. For a large part of the material in the remaining chapters the authors are indebted to the American engineering journals, which are credited throughout, particularly the *Electrical World*, from the columns of which descriptions of plants and results of system investigations and other data have been liberally drawn.

Acknowledgment is especially given to L. N. Crichton of the Westinghouse Electric and Manufacturing Company for the material on installation of protective relays in Chapter VI, which was taken with his permission from a most practical article by him in the *Electric Journal.* The authors are likewise grateful to T. A. Wilkinson, of the Westinghouse

365563

Church Kerr and Company, for permission to use a copyrighted transmission line chart devised by him and a description of his methods for calculating transmission problems. In addition the authors desire to acknowledge an indebtedness to E. P. Peck of the Georgia Railway and Power Company, to M. M. Samuels of the J. G. White Engineering Corporation, to C. A. Mees, formerly designing engineer of the Southern Power Company, and to C. E. Bennett, formerly with C. O. Lenz as consulting engineer, for material incorporated in this book that has been the result of elaborate investigations and research in operating problems. Credit is also given here to all the other engineers whose names appear in the text as investigators and originators of data and information to which reference has been made. To A. M. Perry of the editorial staff of the *Electrical World* acknowledgment is made for helpful suggestions in arranging the material and for assistance in reading the proof.

NEW YORK CITY
January, 1917

WILLIAM T. TAYLOR
DANIEL H. BRAYMER

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UNIV. OF CALIFORNIA

HYDROELECTRIC PRACTICE

CHAPTER I

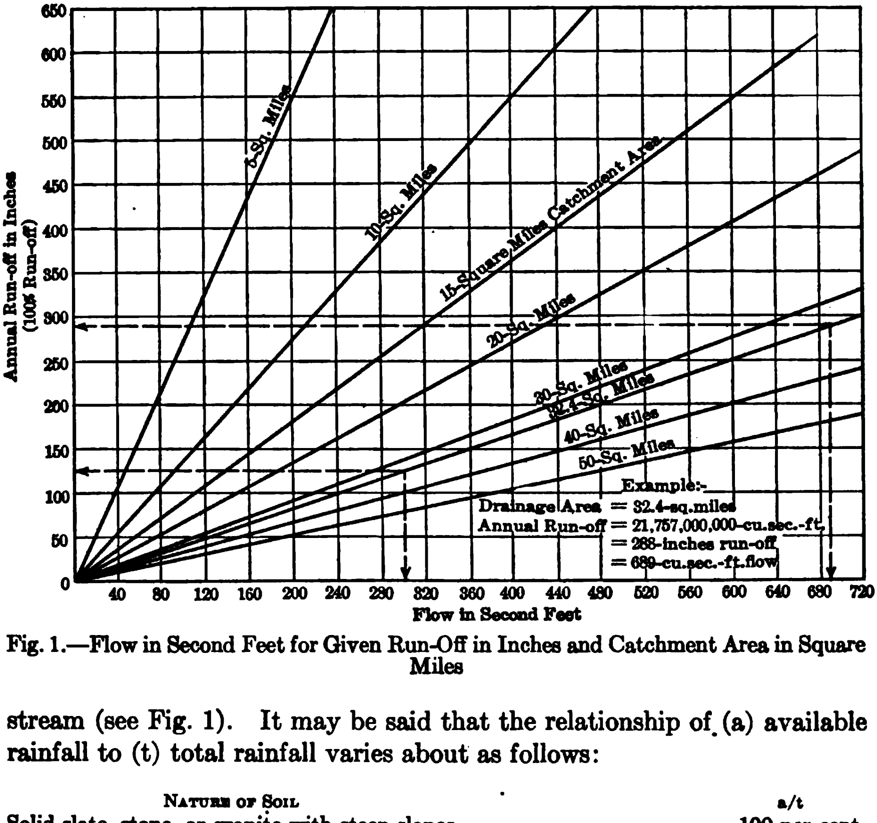
GENERAL SURVEY OF WATER-POWER ENGINEERING

In the investigation of water-power sites, a factor which deserves more attention than has usually been accorded to it, is the variation of rainfall and run-off in different parts of the same watershed or of adjacent watersheds. The time has come when favorably located water-power sites with abundant water are growing increasingly valuable, and the problem before the hydraulic engineer is to make available the largest possible proportion of the rainfall in the territory in which he is working. It is found often that the actual average rainfall over a considerable term of years varies considerably at points on the same watershed or even on the same stream not many miles apart. To get the most out of the stream, therefore, storage space should, if possible, be arranged so as to take advantage of the points of maximum rainfall and presumably maximum run-off. In properly utilizing a given watershed, as can often be done by a group of allied transmission plants, profitable advantage can be taken of local variation. In some instances this has already been done with admirable effect, although, as a rule, insufficient care is exercised in investigating the question. Proper study may show that it is advisable to utilize the flow which accumulates in a given stream not at the obvious points by a single plant, but at two or three points so chosen that the waste-flow may be a minimum.

In several of the largest hydroelectric systems which have been developed in this country the steadying effect of distributed generating stations is very clearly shown, even though the stations themselves have not been planned directly with reference to conjoined operation. Only a beginning, however, has been made to operate along these lines, and it is quite possible to carry it so far as to reduce the waste-water to a very modest amount, except in brief periods of extraordinary floods.

Where storage is impracticable a careful analysis of measurements of stream flow extending over many years' time is absolutely necessary to properly estimate the water-power available. In some part of a large watershed, however, there usually can be found some natural basin for storage of water or an artificial basin may be created to equalize the stream flow as compared with the rainfall. Such a basin is always of great value in regulating stream flow, particularly for medium and high-head plants and even low-head plants. Practically all plants located in industrial centers have periods of low load or no load during the night, hence the water may be stored up for the peak load requirements of the day, and in this manner perhaps 0.5 day sec. ft. of water can be stored over night to give twice the amount of water-power for 10 hours' daily use.

Flow-Summation Curves.—The annual rainfall variations are much greater in some localities than in others. The run-off is that percentage of the rainfall, or inches or feet in depth, which actually gets into the stream (see Fig. 1). It may be said that the relationship of (a) available rainfall to (t) total rainfall varies about as follows:



Example:-
Drainage Area = 32.4-sq.miles
Annual Run-off = 21,757,000,000-cu.sec.-ft.
= 288-inches run-off
= 689-cu.sec.-ft.flow

Fig. 1.—Flow in Second Feet for Given Run-Off in Inches and Catchment Area in Square Miles

Nature of Soil	a/t
Solid slate, stone, or granite with steep slopes	100 per cent.
Cultivated and pasture land, moderate slope	80 to 55 per cent.
Cultivated and pasture land, flat country	48 to 35 per cent.

These figures are affected by the amount of rainfall, the porosity of the ground, the slope of the ground, the surface growth, the temperature and humidity of the air.

So many elements affect the storage of water in a watershed that it is difficult to make at all accurate estimates as to what daily or monthly run-off is to be expected in comparison with the rainfall. The annual ratio of rainfall to run-off is, of course, always more uniform. Where the annual run-off of a stream is extremely variable and storage water is to be carried over in a basin or reservoir from one year to the next, such questions as proper regulation of stream flow and storage are better solved by means of the summation curve method, thus doing away with much tiresome calculation, and solving difficult problems almost at a glance. By its use many such rather difficult problems as the following can be quickly solved: (a) Having the mean hourly or daily discharges of a stream, how large a reservoir is required to obtain maximum regulated flow? (b) Having a certain reservoir capacity and the mean hourly or daily discharges of a stream for a period of months or years, what is the maximum regulated flow which can be obtained for water-power? (c) Having the mean daily discharges of a stream, a certain portion of which is already appropriated for direct use for irrigation, how much of the stream flow is available as storage for water-power purposes? A summation curve (summation of the mean daily discharges) for a given case is shown in Fig. 2.

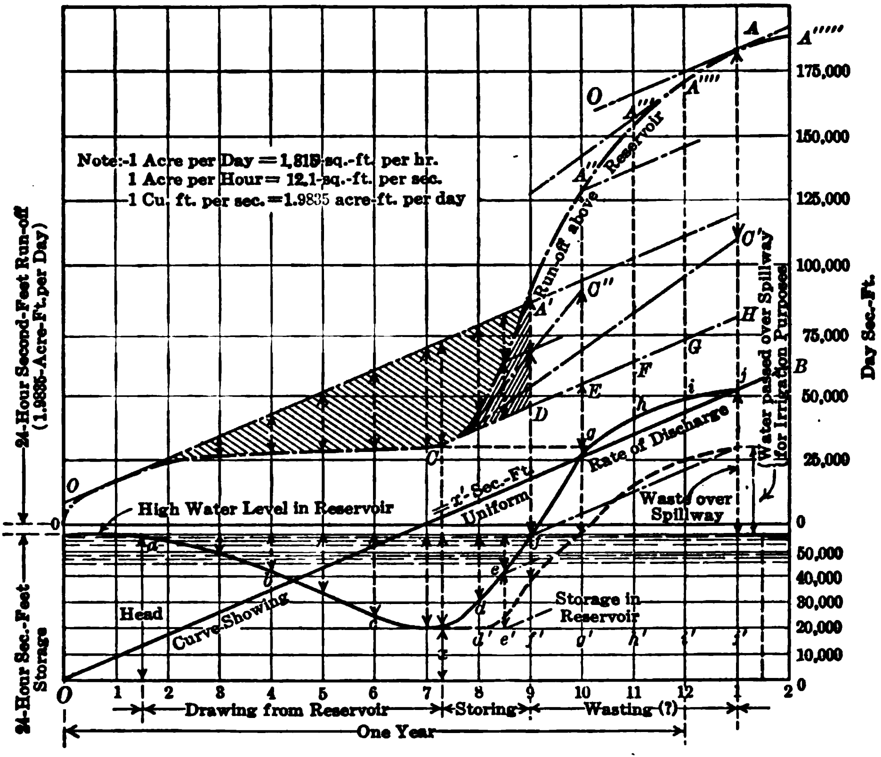


Fig. 2.—Flow-Summation Curve for Storage and Stream Regulation

Take the case of a medium size and medium-head hydroelectric development offering storage features by use of a natural lake which has an area of 3.1 sq. miles, or 86,423,040 sq. ft., requiring 20 ft. in depth at this area to provide for the required storage. Water measurements for eight months and an estimate for the remaining four months give a yearly run-off of 21,757,000,000 cu. ft., and as the drainage (catchment) area is 32.4 sq. miles, this run-off amounts to 24 ft. (288 in.), or an equalizing annual flow of 689 cu. sec. ft. However, the initial plant requires only 300 cu. sec. ft., equivalent to a run-off of 10.4 ft. (124.8 in.) (see Fig. 1). To be certain of 300 cu. sec. ft. continuous flow, a lake is drawn on by tapping with a tunnel to a depth of 12 ft., and the spillway from the lake closed, thus raising the lake level 25 ft., giving an available storage of 12+25=37 ft. There are two steel pipe lines, each of 60 in. diam. and 2000 ft. in length. The velocity of flow in each pipe is 8 ft. per sec. The head-loss is 4.5 ft. for the 2000 ft. of pipe, or 2.25 ft. per 1000 ft. The pipes are 0.187 in. thick at their upper ends and 0.75 in. thick at their lower ends. The power-house is situated 535 ft. below the lake. It contains one 5,000 kw. unit direct connected to a water turbine utilizing 300 cu. sec. ft. with provision for a duplicate unit.

From actual stream-flow measurements taken at regular time-periods in second feet (cu. ft. per sec.) units of flow, the following figures were obtained, the summation of which may be reduced to units of day second feet (sec. ft. flow during 24 hours = 1.9835 acre ft.), or any other convenient units of flow and a summation curve plotted. The elements of such a curve are shown in Fig. 2.

The following physical data is for a certain development to which the flow-summation curve application refers:

Drainage Area = 32.4 sq. miles.
Annual Run-off = 21,757,000,000 cu. ft.
= 288 in. run-off.
= 689 sec. ft., annual stream flow.
Initial Requirements are for 300 sec. ft. = 124.8 in. run-off.
Annual Flow Required for 300 sec. ft. = 9,460,800,000 cu. ft.
Annual Flow Required from Storage Reservoir for the 300 sec. ft. Constant Power Demand = 2,510,210,200 cu. ft.

TABLE 1.—STREAM-FLOW MEASUREMENTS FOR A PARTICULAR SITE.

MONTHS OF THE YEAR	MEASURED STREAM FLOW	REQUIRED FLOW FOR 300 SEC. FT.	DRAWN FROM THE NATURAL LAKE
January	324,187,200	803,520,000	479,332,800
February	283,046,400	727,760,000	442,713,600
March	374,976,000	803,520,000	424,544,000
April	352,512,000	777,600,000	425,088,000
May	1,154,390,000	803,520,000	....
June	2,947,104,000	777,600,000	....
July	5,340,729,600	803,520,000	....
August	4,860,492,480	803,520,000	....
September	4,473,792,000	777,600,000	....
October	803,520,000	803,520,000	....
November	518,400,000	777,600,000	259,200,000
December	324,187,200	803,520,000	479,331,800

HYDROELECTRIC DEVELOPMENT COSTS:

Closing of spillways from lake	$10,000
Tapping of lake	5,000
Pipe lines (two 60 inch) with head-gates	93,600
Power-house with two 5,000 kw. units complete	250,000
Contingencies and incidentals	3,000
Construction plant	13,880
Total cost	$375,480

$375,480 ÷ 10,000 = $37.54 per kw. capital cost.
= $27.25 per hp. capital cost.

OPERATING COSTS (yearly costs):

General expense	$6,000
Labor for operation	6,000
Supplies, etc.	4,000
Total cost of operation	$16,000

Then,

$16,000 ÷ 10,000 = $1.60 per kw. year.

Considering eight per cent. of capital cost as covering interest and depreciation, $37.50 × 0.08 = $3.00; which makes the total operating cost $4.60 per kw. year, or $3.45 per hp. year.

Layout and Use of Flow-Summation Curve.—In Fig. 2 the flow measurements which represent the total quantity of water per 24 hours (sec. ft.) are plotted as ordinates, the units of time being plotted as abscissas; that is, the sum total of any date represents the total quantity of water which has flowed past the gaging station up to that date and is shown by the run-off curve. Let us assume, for example, that the rate of discharge is uniform; that is, in the case given the uniform rate of regulated flow is for 300 sec. ft. Then by applying the curve for uniform rate of discharge as a tangent to the summation curve at *A* it can be shown that for this particular curve the stream from about the beginning of month (1) began to discharge less than this flow and did not rise above that quantity until about the middle of month (7).

Let *OA* represent the measured stream flow, which is, as stated above, that percentage of the rainfall or inches depth of run-off which actually gets into the rivers or streams; *OB* is the required regulated flow. Starting with a full reservoir in month (1), the summation curve shows that the stream flow is below the required regulated flow *OA′*, parallel to *OB*, and that the cross-hatched area shows the amounts of storage required to maintain the regulation. Plotting these required amounts below the high-water level of the reservoir (in the storage diagram), the storage curve *abc* is obtained, showing the behavior of the reservoir during the uniform rate of discharge for power purposes. At *C* the summation curve shows that the stream flow is above the required regulated flow; consequently *CDA′*, the cross-hatched section, represents the amount of water which can be stored until the reservoir is full (see the storage curve *dd′*, *ee′*, and *ff′*).

Continuing this plotting of the summation curve as $A''E$, $A'''F$, $A''''G$, etc., the quantity of water going to waste (passing over the reservoir spillway) is obtained, which is shown at *ghi* and *j*. If it is desired to know how large a reservoir is required to obtain a maximum regulated flow, knowing the mean discharges of the stream, the line CC' may be drawn from which the ordinate AC' represents the capacity of the reservoir necessary to effect maximum regulated flow when using all the water available. The line EC'' shows the quantity of water taken from the reservoir for irrigation purposes, and *Eg* the quantity of water from the tail-race which is also available for irrigation purposes. To obtain accurate results, the summation curve should be plotted to a large scale and as flat as possible, so that the point of tangent for slopes of different ratios of flow can be readily detected.

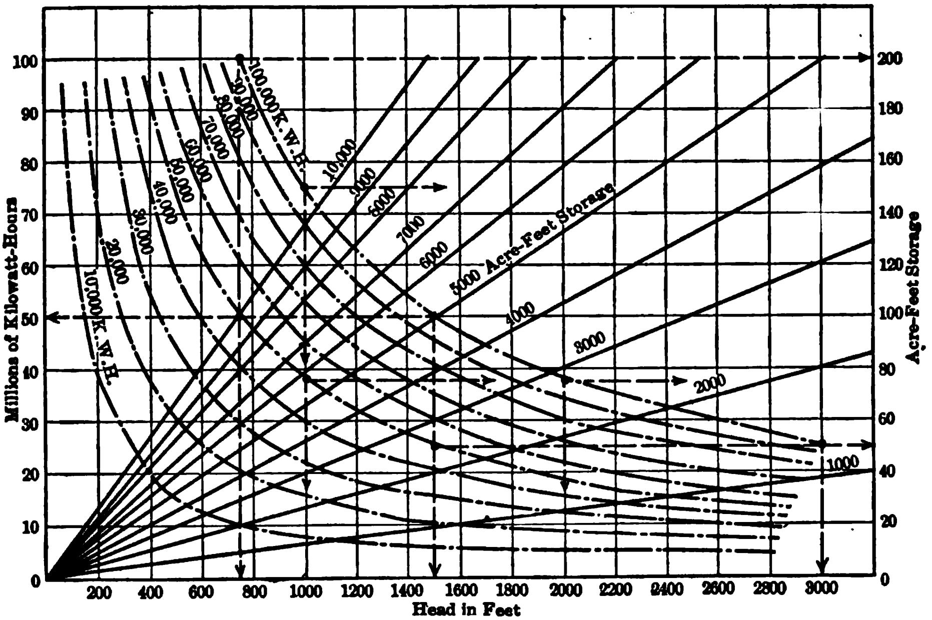


Fig. 3.—Storage Capacity in Acre-feet and Kilowatt-hours for Various Heads in Feet

To gain the fullest advantage, provision must be made for feeding energy to a network mainly from one or another of its generating stations according to the hydraulic situation. What is true of plants operating on a single watershed is doubly true of plants operating on separate watersheds, in which the flow may differ very widely. In either case it may readily happen that two streams of very different hydraulic quality can be united to their mutual advantage, as, for example, when one stream is fed largely by springs and diffuse drainage and another by melting snow. The plants of a system should be operated as a whole, shifting the load whenever it will save water.

Value of Water Storage.—The value of water storage for hydroelectric purposes is daily becoming of greater importance. With a stream flow of, say, 60,000 cu. ft. per min., assuming that the head with this flow remains fixed for 10 hours during the 24 hours of each day, if a storage reservoir be built large enough to retain the 60,000 min. ft. flow for 14 hours during the 24, the turbines in the generating station will be in a position to develop the stored energy of the water for the 10 hours and also the amount flowing during the 14 hours.

The actual importance of water storage is better understood from practical examples. Assume a dam which provides a water space of 50 acres and a mean depth of 10 ft. to be drawn on, the average head of plant being 1,500 ft. What kw. capacity does this represent for 10 hours' operation?

With water used at 100 per cent. efficiency, one acre ft. of water under one ft. head equals 1.025 kw. hr. Then,

$$10 \times 1{,}500 \times 1.025 = 15{,}375 \text{ kw. hr. per acre of storage capacity, or}$$
$$15{,}375 \times 50 = 768{,}750 \text{ kw. hr.}$$

for a storage capacity of 50 acres at 10 ft. mean depth, which at 65 per cent. efficiency (hydroelectric) is (see Fig. 3):

$768{,}750 \times 0.65 = 499{,}687$ kw. hr. or practically 500,000. Then for 10 hours' operation, we have

$768{,}750 \div 10 = 76{,}875$ kw. available capacity at 100 per cent. efficiency of water, or

$76{,}875 \times 0.65 = 50{,}000$ kw. at the hydroelectric efficiency of the plant, or 67,000 hp.

By expressing kw. hr. and hp. hr. in terms of cubic feet of water stored we obtain the following formulæ,

$$\text{Kw. hr.} = \frac{H \times s}{42{,}466} \text{ and hp. hr.} = \frac{H \times s}{31{,}680} \text{ at 100 per cent. efficiency,}$$

where (s) is the amount of water in cu. ft. stored for use and (H) is the average head of the plant. Thus, for the above example we find the stored energy to be as follows, considering: one acre ft. per second is equal to 43,560 sec. ft., and for the 50 acres in question, assuming hydroelectric efficiency at 65 per cent., we have, $50 \times 43{,}560 = 2{,}178{,}000$ sec. ft., hence:

$$\frac{1{,}500 \times 2{,}178{,}000 \times 0.65}{42{,}466} = 50{,}000 \text{ kw.}$$

and

$$\frac{1{,}500 \times 2{,}178{,}000 \times 0.65}{31{,}680} = 67{,}000 \text{ hp.}$$

The unit of flow most used is that of cubic feet per minute or per second.

In view of this a series of curves has been plotted (Fig. 4) showing electrical energy in kw. per cu. ft. per minute for various hydroelectric efficiencies ranging from 50 per cent. to 100 per cent. under varying heads in feet. It will be noted that the position of these curves remains fixed for any lower or higher values, as in Table 2.

TABLE 2.—ENERGY STORED IN WATER AT VARIOUS HEADS (s' and s'' equal unity.)

HEAD IN FT.	HP. HR. VALUES	KW. HR. VALUES	KW. IN WATER
10	13,75	10.25	0.0141
100	137.50	102.50	0.141
1000	1375.00	1025.00	1.41
15	20.62	15.37	0.0212
150	206.20	153.70	0.212
1500	2062.00	1537.00	2.12
32	44.00	32.80	0.0452
320	440.00	328.00	0.452
3200	4400.00	3280.00	4.52
55	75.62	56.37	0.0777
550	756.20	563.70	0.777
5500	7562.00	5637.00	7.77

(Values are for 100 per cent. efficiency)

where Kw. hr. values $= 1.025\,H \times s'$

and Hp. hr. values $= 1.375\,H \times s'$

and Kw. in water $= H \times s'' \div 707.7$

Hp. in water $= H \times s'' \div 528$

The factor s' is for acre ft. values, and s'' is cu. ft. per minute.

Effective Head.—In Fig. 5 the total head is shown as $O'H'$ and the effective head somewhat less indicated as OH. When the value of OH is known, the velocity and the discharge can be calculated. To arrive at the value of OH the head lost must be ascertained. When a pipe line is to be considered, the friction of the pipe causes the greatest loss of head and is quite independent of the inclination of the pipe. There are also minor losses, such as loss of head due to velocity and entry loss. The former is best explained as a loss in causing the water to take up the velocity in the pipe or in energy of motion,

$$v^2/2g = v^2/64.4;\ \text{hence}\ H_v = v^2 \times 0.0155.$$

The entry loss varies in amount with the form of the orifice. The theoretical velocity with which water flows from an orifice in the side of a reservoir or vessel at a depth H from the surface is the same as that of a body falling freely by gravity from a height H so that, $v = \sqrt{2gH}$. In practice, however, the converging currents produce contraction of the jet of water and the velocity of discharge is modified. This is taken into consideration by the use of a proper coefficient whose value varies with the nature of the orifice.

From a general form of Bernoulli's theorem the following equation is derived for the total head at any point,

$$H = p + e + v^2/2g,$$

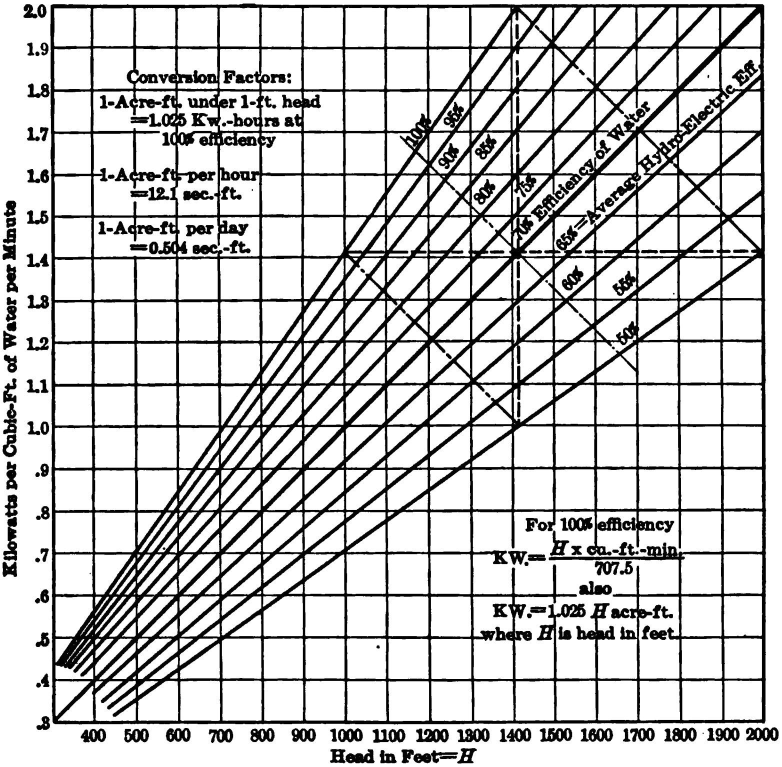


Fig. 4.—Kilowatts per Cu. Ft. of Water per Min. for Efficiencies from 50 per cent. to 100 per cent. Under Varying Heads

where p is the pressure head or the height of a column of water necessary to produce the pressure at the point; e is the elevation of the point above an arbitrary datum plane, and $v^2/2g$ the velocity head as already explained. According to Bernoulli's theorem, for a steady flow from an up-stream position n to a down-stream position m, the head $H_m = H_n$—[all losses of head between n and m]. In this formula H_m and H_n are total heads, and

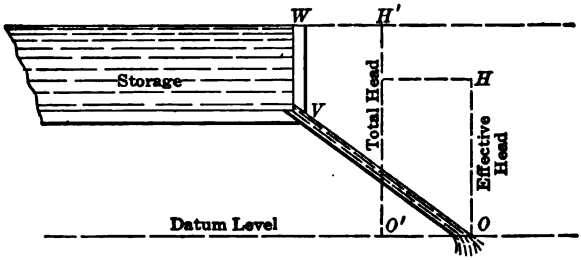


Fig. 5.—Total and Effective Heads of a Development

for all practical purposes where a long pipe is considered the losses other than pipe friction can be neglected. The loss due to pipe friction may be considered,

$$h = K\frac{lv^2}{d2g}$$

K is a coefficient for pipe friction which has been determined by different investigators and found to decrease as the velocity increases and as the diameter increases and increases with the roughness of the pipe. The length of the pipe is represented as l, its diameter by d, and v the velocity of the water in the pipe.

Other working formulae for frictional loss are given under the heading of "Friction Loss in Pipes" and further references to head under "Effective Head of a Development."

Penstock Losses.—The foundation for all calculations of a water-conduit or penstock should be on the basis of conduit-grade and the amount of power wasted due to the grade. For every foot length saved in length of water-conduit there is a saving in head loss, in evaporation and in seepage losses. In the past much time has been devoted to economy and character of materials, etc., and the conduit-grade was decided on in a rule-of-thumb method or accepted on the basis of a preceding development with little knowledge as to power losses due to the grade.

On a somewhat similar basis to that of Kelvin's Law for the most economical conductor cross-section, a law for the most economical conduit section may be employed which may be stated as follows:

The most economical area of conduit is that for which the annual cost of wasted energy is equal to the annual interest on that portion of the capital invested. That is to say, the capacity of conduit in second feet, velocities in sec. ft., grade in feet per 1000, the hp. loss due to the grade should equal the fixed charges on the investment of the conduit.

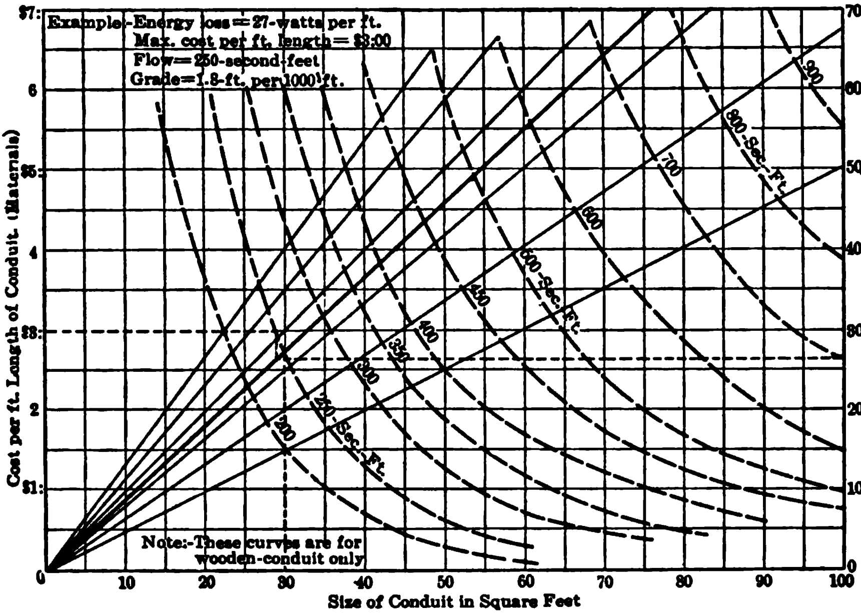
Every kilowatt lost per year is a dead loss. In a water-conduit it is a loss that will never decrease in value and one that will remain a loss as long as the development is in existence. A conduit once given its grade and constructed, cannot very well be changed except at a very great expense; thus it behooves engineers to look not only to economy of design, but to the highest efficiency for a given economy.

In the construction of a conduit several important factors have first of all to be considered:

(a) The grade.
(b) Hydraulic mean radius.
(c) Coefficient of roughness.
(d) The conduit-form, etc.

The grade will depend on several conditions. In the first place the character of the ground will place certain limits on the velocity of flow, which must not be so great as to injure the conduit-bed. The grade necessary to maintain the velocity within the desired limit will also depend on the character of the interior surface of the conduit, being less for a smoother surface. The form and area of cross-section also affects the grade, because they affect the velocity of flow—in other words, there will exist a loss in kilowatts due to the grade, and the conduit-form, coefficient of roughness, and mean hydraulic radius are but affected parts due to the grade.

Should the character of the ground (conduit-bed) be of such a quality, for the major part thereof, as to limit the velocity of water, the next nearest grade with the least effect on the kw. loss, should be adopted. In Fig. 6 it is shown that, for a given capacity in cubic feet seconds (any other measure can be employed if desired), with the sale price of energy per kw. year fixed and the purchase price of materials for building the conduit fixed, the most economical section may readily be found by simply comparing the difference in energy sales (kw. year loss) with the difference in yearly costs (fixed charges). This reasoning applies to all kinds of water-conduits, whether closed or open.



Note:-It will be noted that these curves follow the principal of Kelvin's Law shown in Fig. 158

Fig. 6.—Curves for Determining the Most Economical Size of Water Conduit

To illustrate these considerations, reference will be made to a practical case, the values of which are taken from actual practice and plotted to curves after having figured the average cost of materials per lineal ft. of conduit, and the watts loss per lineal ft. The materials costs in this particular case include lumber (board ft. measure) per lineal ft., cu. yds. of excavation per lineal ft., and lbs. of nails per lineal ft. for different sizes of conduit in sq. ft. at different stream flow in cu. ft. per second. In a concrete case which gives the most economic conduit section for a given capacity, the following factors were involved:

Capacity in sec. ft.	250 sec. ft. flow.
Conduit grade	1.8 ft. per 1000 ft.
Annual fixed charges	$3.00 (max.) per ft.
Watts loss due to grade	27 watts per ft.
Conduit Area	30 sq. ft.

It is, of course, apparent that a choice for a stream flow of 250 sec. ft. can be made between a 20, 30, 40, 50, etc., sq. ft. section conduit, but the question here is—at what economic cost? For a flow-capacity of 250 sec. ft. there is a choice between the following values which make for the most economical conduit cross-section:

Materials Cost Item (Conduit section in sq. ft.)	Energy Sales Loss Item (Kilowatts per 1000 ft.)
20	78.00
30	27.00
40	12.90
50	7.05
60	4.38
70	3.00
80	2.10
90	1.50
100	1.20

Thus, if we assume a fixed amount for the kw. loss per year and a fixed price for the materials to complete the conduit, the most economic conduit section is that giving the least difference, that is, where one equals the other or nearest thereto. The curves of Fig. 6 enable the most economical conduit cross-section to be quickly determined. For this case it is 30 sq. ft., this being the nearest to where the two curves intersect each other. With lumber in place as $30 per 1000 ft.; excavation at $0.25 per cu. yd.; and nails at $0.015 per lb., we arrive at the following relative costs for different section areas of conduits:

Table 3.—Relative Costs for Different Section Areas of Conduits.

Conduit Section Area in Sq. Ft.	Lumber Cost Per 1000 Ft.	Excavation at (6 Per Cent. of Cost)	Nails at (8 Per Cent. of Cost)	Total Cost
20	$1547.00	$93.00	$123.75	$1763.75
30	2257.00	136.50	180.50	2574.00
40	2625.50	177.00	210.00	3012.50
50	3211.00	192.00	257.00	3660.00
60	3681.00	221.00	295.00	4197.00
70	4489.00	269.00	359.00	5117.00
80	4962.00	298.00	397.00	5657.00
90	5353.00	321.00	426.00	6100.00
100	6173.00	370.00	494.00	7037.00

Assume further that the sale price of electrical energy is at the rate of $45.00 per kw. year, then we find the relative difference to be—

Conduit Section Area (Sq. Ft.)	Energy Sales Loss (Relative Values per Kw. Year)	Total Materials (Annual Fixed Charges)	Relative Difference
20	$3510.00	$1763.75	$1746.25
30	1215.00	2574.00	1359.00
40	580.00	3012.50	2532.50
50	317.00	3660.00	3343.00
60	197.00	4197.00	4000.00
70	135.00	5117.00	4982.00
80	94.00	5657.00	5563.00
90	67.00	6100.00	6033.00
100	54.00	7037.00	6983.00

The most economical section area is therefore shown to be 30 sq. ft.

It is obvious that for every foot saved in length of conduit there is a saving in head loss as well as in evaporation and seepage losses. To properly illustrate the importance of these losses consider the following example: 1000 ft. of conduit of 50 sec. ft. capacity installed on a grade of 1 ft. in 1000 ft. Then, 1000 ft. of conduit dissipates 1 ft. head, and, with a discharge of 50 sec. ft. and assuming combined efficiency to be 65 per cent., we have

$$\frac{1\times 50\times 62.4\times 0.65}{550}=3.7 \text{ hp. head loss or}$$

2.75 kw. head loss.

Assuming the rate for electrical energy as $50 per kw. yr., then the loss due to head is $2.75\times 50=\$137.50$.

Taking evaporation on the basis of five ft. per year, we shall have approximately 0.9 acre ft. per year or 0.0025 acre ft. every 24 hours, which is equal to 0.00125 sec. ft. Therefore, for a plant with a head of 1,650 ft., loss due to evaporation would represent

$$\frac{1{,}650\times 62.4\times 0.65\times 0.00125}{550}=0.152 \text{ hp. or a}$$

0.113 kw. evaporation loss. At $50 per kw. yr. this would be $0.113\times 50=$ $5.65.

The rate of percolation will depend on the kind of conduit, its condition and other things. However, for calculation, assume that, under a head of 3.5 ft. the conduit will have a seepage loss of about 0.004 ft. per hour or 0.009 sec. ft., then the loss due to percolation will be

$$\frac{1{,}650\times 62.4\times 0.65\times 0.009}{550}=1.1 \text{ hp. or a}$$

0.82 kw. seepage loss. At $50 per kw. yr., this will be $0.82\times 50=\$41.00$.

Then, the total energy loss per year represents a revenue loss of $137.50+5.65+41.0=\$184.15$ per 1000 ft. of conduit, or a loss of $0.184 per ft. length of conduit.

Pipe Line Considerations.—Although much has been added in recent years to our knowledge of the phenomena of flow of water in pipes, practical data are still in a very imperfect state. While allowances are always made for loss of head due to sharp bends or curves, valves or other obstructions, entry losses, etc., allowance should also be made for the reduction in pipe size due to deposits of silt, and air mixed with water. The remedy for silt deposits is evident, but the air problem is not so simple. Air reliefs located at summits in a pipe do not give ample help. The most correct remedy is to capture the air at the intake and prevent it from entering the pipe. If this is not possible, adequate air-reliefs should be located just below the intake, so as to minimize the amount of air carried through the pipe with the water. It is difficult to emphasize too strongly this air problem as affecting the flow of water in pipes, and, it is not unlikely that this may explain some of the vagaries in experiments which have been made in the past and affecting our present day formulæ.

In pipe lines not well proportioned with reference to diameter, thickness of material, bends and connections, the efficiency will be greatly impaired and much trouble likely to result. This important part of a hydroelectric plant may also, due to wrong design, cause disturbances in the plant's operation and have a very serious effect on the proper utilization of the water-power. In planing a pipe line it should therefore be kept in mind that the following are important factors: the most suitable form and arrangement of inlet at the forebay at sufficient depth below the lowest water-level; the right slope to the pipe line; that it should be made as straight as possible; that it should be strongly supported and anchored and backed to secure it against any movement due to the action of the water; proper allowance for expansion joints to take care of expansion and contraction due to changes of temperature, etc.; that no undue pressure of the pipe line is put on the forebay, power-house nor the units in the generating station; and, that proper calculations are made so that the velocity of water will not rise above the limit and strength of the pipe—making due allowance for rough handling and effects due to sudden stoppage of flow.

Friction Loss in Pipes.—The frictional loss in the flow of water along a pipe line has been determined on the assumption that the pipes are clean, are of uniform diameter and have regular alignment, profile, etc. In general, even for a newly laid pipe line this is not realized, in fact it is not always possible to keep the core perfectly central throughout a pipe line, for a pipe may have an excess of metal on one side and a corresponding deficiency on the other side. Formulæ for this loss (friction loss) are very numerous, but a reliable one is as follows:

$$H = \frac{0.38\, v^{1.86}}{d^{1.25}}$$

Where H is friction loss per 1000 ft. of pipe, d is diam. in ft.; and v is mean velocity of flow in ft. per second. (*Trans. A. S. C. E.*, Vol. 51, page 308.)

Likewise a great variety of formulæ have been proposed for mean velocity as $v=c\sqrt{RS}$. (Chézy's formula) where R is the hydraulic radius (cross-sectional area ÷ wetted perimeter); S the hydraulic slope (loss of head in ft. per ft. of length or the surface fall for open channels); and c is a coefficient which may be considered as 100 for moderate roughness of pipe or channel.

In none of the generally used formulæ has any allowance been made for such important factors as loss of head due to sharp bends or curves, valves or other obstructions, entry losses, etc., hence additional allowance must be made in all cases. The importance of these allowances can be better understood from the following concrete case:

Length of pipe line = 15,865 ft. (wood-stave pipe)
Diameter of pipe = 68 in. (inside diam.)
Slope for 10 ft./sec. = 4 ft. in 1000 ft.

This pipe contains five steel bends where the curvature is greater than 20 deg. These bends are made to a 15 ft. radius and have angles of 92, 55, 65, 60 and 45 degrees respectively. The loss in head for each bend as measured by a differential pressure gage is given in Table 4.

TABLE 4.—ENTRY AND BEND LOSSES AT DIFFERENT VELOCITIES

VELOCITY FT./SEC.	LOSS IN ENTRY	BENDS					TOTAL LOSS IN PIPE	LOSS PER 1000 FT.	FRICTION LOSS AFTER DEDUCTING ENTRY AND BENDS LOSSES
		No. 1 (92) deg.	No. 2 (55) deg.	No. 3 (60) deg.	No. 4 (65) deg.	No. 5 (45) deg.			
2.5	0.06	0.03	0.03	0.03	0.03	0.01	4.1	0.246	3.91
5.0	0.25	0.09	0.08	0.08	0.08	0.05	15.4	0.931	14.77
7.5	0.54	0.25	0.18	0.19	0.20	0.14	33.9	2.042	32.40
10.0	1.14	0.46	0.34	0.36	0.37	0.27	61.9	3.775	58.96

For the flow of water in pipes the exponential formula or constant coefficient formula, as it is often called, should preferably be used, thus doing away with tiresome calculations for coefficient values or the use of tables of coefficient = c which, in this formula are not required; that is, for formula Q = discharge in sec. ft., it is better to apply

(a) $Q=1.35\ h^{0.55}\ d^{2.7}$ (for wood-stave pipe)
(b) $Q=1.31\ h^{0.55}\ d^{2.7}$ (for cast-iron pipe)
(c) $Q=1.18\ h^{0.55}\ d^{2.7}$ (for riveted-steel pipe)

(a) This formula may also be used for the continuous concrete pipe.
(b) This formula may also be used for the so-called concrete (wet-mix) jointed-pipe.
(c) This formula may also be used for the so-called concrete (dry-mix) jointed-pipe.

In these formulæ h is expressed in friction-loss per 1000 ft. of pipe with d the diameter of pipe in ft. (Moritz, U. S. Reclamation Service practice.)

Formulæ for $v=c\sqrt{RS}$ have been used a long time and still are being proposed and added to reference text-books. A more practical constant coefficient formula (Flamant) is

$$v=86.38\ S^{0.57}\ d^{0.715} \qquad \text{(for new cast-iron pipes)}$$
$$v=76.28\ S^{0.57}\ d^{0.715} \qquad \text{(for old cast-iron pipes)}$$

Allowances should always be made for the deterioration of cast-iron pipe with age, the formula for which is

$$Y=\left(\frac{1-n}{1200d}\right)^{2.69}\times\left(\frac{1}{1+0.03n}\right)^{0.55}$$

where it is assumed that the friction-head increases 3 per cent. per year due to tuberculation, and that the diameter of the pipe decreases 0.01 inch per year from the same cause. Y equals the ratio of discharge when the pipe is n-years old to the discharge when the pipe is new.

Economical Diameter of a Pipe Line.—In large, long pipe lines the determination of the most advantageous velocity, or in other words, the fixing of the diameter, is subject to very close calculations. The proper dimensions of a pipe, and also the cost of a pipe, will be higher the lower the velocity for a given case. The material may be of wood, cast-iron, riveted-steel pipe or concrete pipe (wet-mix jointed or dry-mix), etc.

A much used formula which gives a close approximation of the economical diameter of pipe lines (*Engineering Record*, November 14, 1908) follows,

$$D=3.14\ (Q\div\sqrt{S})^{\frac{2}{5}}$$

where D is the diameter in inches, Q is the flow in sec. ft., and S is the slope. This formula is suitable for large diameter steel pipes and for penstocks.

A. L. Adams has shown (*Trans. A. S. C. E.*, Vol. 59, page 177) that a pipe fulfils the requirements of greatest economy when the value of the energy lost in frictional resistance equals four-tenths (0.4) of the annual cost of the pipe line. The cost is assumed to be proportional to the weight of metal and that the loss of head due to frictional resistance varies as the square of the velocity of water in the penstock. This theorem holds true for riveted steel pipe but not for wood-stave or cast iron pipe. If then L is the value of energy lost by frictional resistance and C the annual cost of the pipe line, (interest on cost of pipe, construction and depreciation),

$$L=0.4\ C \text{ for economical design.}$$

The horsepower used to overcome frictional resistance per foot of penstock when the quantity being discharged is Q sec. ft. is,

$$\text{Hp}=183{,}400\ Q^3\div c^2d^5$$

where c is the coefficient in Chézy's formula, and may be taken as 120 for wood-stave pipe, 130 for new cast-iron pipe and about 100 for old cast-iron and riveted pipe; d is the economical diameter of the penstock section in inches (*Engineering Record*, September 12, 1914).

Another formula that is convenient in checking economical pipe sizes is,

$$D = 13.5 \quad (e/5)^{0.138} \ Q^{1/2.3}$$

where D is the diameter in inches; Q the quantity of water delivered in million gallons per 24 hours and e is the cost of raising 1,000,000 gallons of water one foot high and may be taken at about 5 cents (*Engineering Record*, December 27, 1913).

Practice has shown that wooden penstocks may be successfully used for heads up to 300 feet. Seasoned or kiln-dried yellow pine, redwood or fir are suitable for wood-staves. For the spacing of iron bands the formula by J. D. Schuyler (*Trans. A. S. C. E.*, Vol. 31) may be employed,

$$N = 1200 \ DP \div 2 \ S$$

where N is the number of bands per 100 feet, D the diameter of the pipe in inches; P the pressure in lbs. per sq. ft. and S the safe working strain in bands in lbs. per sq. in. A factor of safety of 5 is usually advisable.

Since commercial sizes of pipes must in most cases be used, a "cut and try" method in solving pipe diameters with the aid of the formulas given will usually be most convenient and satisfactory for ordinary conditions and moderate heads. In this method a reasonable diameter is assumed and the rate of discharge that this diameter would give computed. If this value is too large or too small when compared with the rate of discharge required, a new size is assumed and the calculation repeated until the proper size is found. In this method it must be remembered that with an increase in size of pipe there is a variation in velocity of flow such that a pipe somewhat larger than another will discharge more in proportion to its area than the smaller size. In assuming sizes therefore this point must be considered.

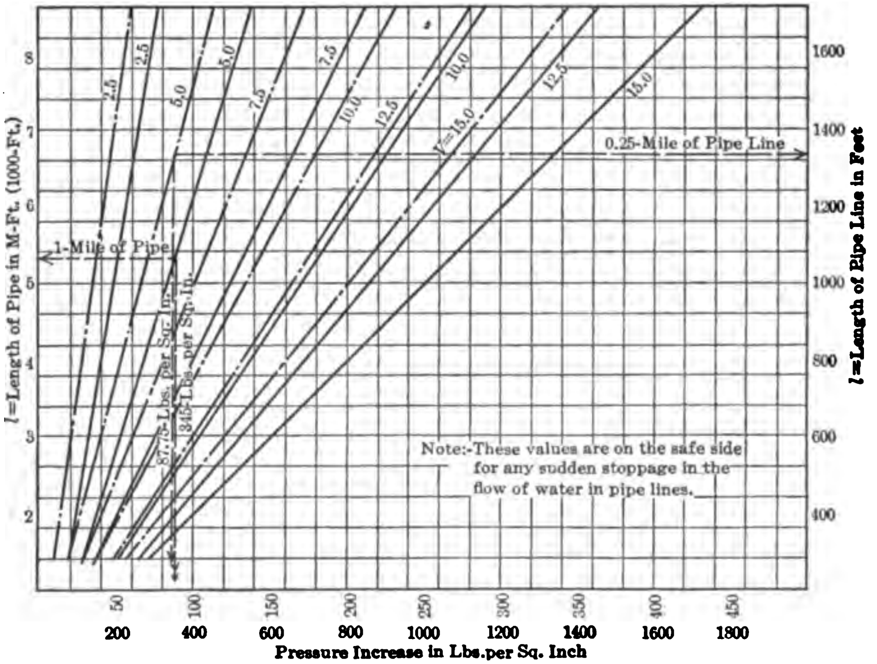
The great pressure of water in high head plants requires careful engineering to prevent trouble. It involves no difficulty to take care of stress and deformation of the lower part of a pipe line with its valves and connections, but the control of the water is a serious problem. To properly illustrate its magnitude consider what might be called at the present time a medium-head and power development. For a 60 in. diam. pipe of 5,000 ft. in length with a velocity of eight ft. per second operating under a head of 400 ft., producing slightly over 5,000 hp., the actual weight of water in the pipe line will be more than over 3,000 tons. Representing this weight in the order of a moving freight train, it compares with a weight nearly equal that of a loaded freight train half a mile long. This, in itself and under normal conditions, is very easily taken care of, in fact, every-day design demands it. But what would happen if the train were brought to a stand-still in say, one second or even two seconds, or accelerated instantly to a speed of eight ft. per second from rest?

Water Hammer.—Just what the actual initial pressure (extra stress) is, caused by a sudden closing of the valves due to the entire 5,000 hp. being thrown off, is not easily determined, but it can be approximately expressed as

$$p_s = v\,V \div g \qquad \text{(feet of water)}$$

$$= \frac{62.5\,v\,V}{144 \times 32.2}$$

$$= .0134\,v\,V \qquad \text{(lb. per sq. in.)}$$



Note:-These values are on the safe side for any sudden stoppage in the flow of water in pipe lines.

Fig. 7.—Curves Showing Pressure Increase for Various Lengths of Pipe Line and Retardation of Flow of Water at Various Velocities for Different Time Periods in Seconds

In these formulas p_s is the excess pressure due to the water hammer, v is the original velocity of the water in the pipe, V is the velocity of the pressure wave in ft. per sec. and g is 32.2. The value of V is closely approximated by the following formula (Daugherty):

$$V = 4700\sqrt{\frac{E}{E + 300{,}000\frac{d}{t}}}$$

where E is the modulus of elasticity in tension of the material composing the pipe in lb. per sq. in. and d/t is the ratio of the pipe diameter to thickness of walls. For steel E may be taken as 30,000,000 lb. per sq. in.; for cast iron, 15,000,000 lb. per sq. in.; for wood, 1,500,000 lb. per sq. in.

The hoop tension in the wall of the pipe due to the excess pressure p_e is,

$$p_h = r\ p_e \div t$$

where p_h is in lb. per sq. in., r the radius of the pipe in in., p_e the excess pressure in lb. per sq. in., and t the thickness of the pipe wall in inches.

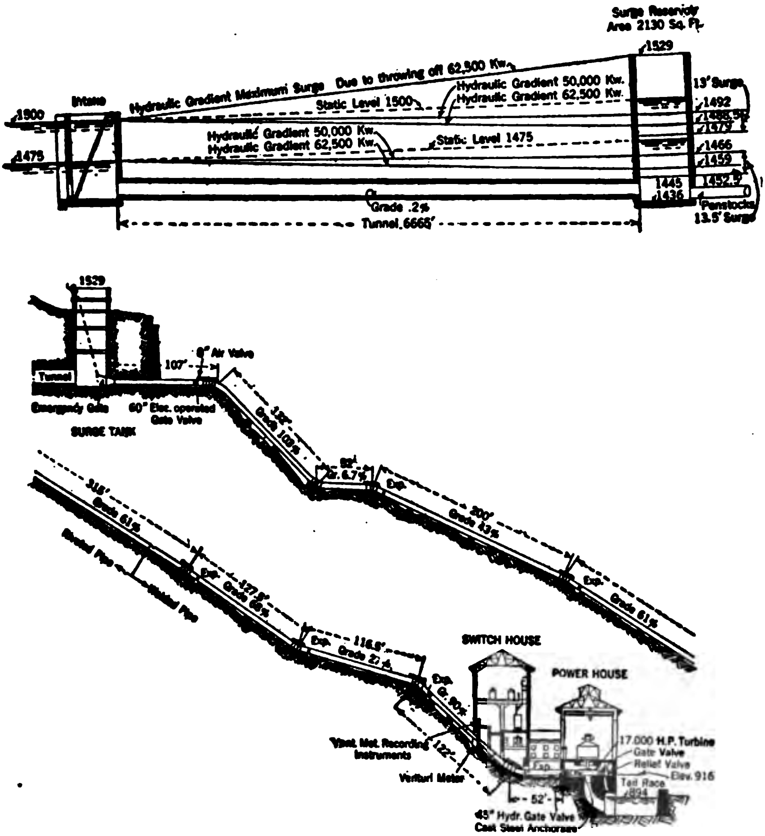


Fig. 8.—Features of Surge Tank and Penstocks for the 72,000 Kw. Development of Georgia Railway and Power Company

The time taken for the pressure wave to travel the length of pipe is, $t_1 = l \div V$, and the time required to travel from one end to the other and back is twice this or $t_2 = 2l \div V$. The full value of p_e would not be produced, therefore, unless the time of closing the valve is less than t_2. The valves in a long pipe line must move to the required position without oscillation to prevent water hammer and must also open very quickly, and the time of closing must be long as compared with the vibration pitch of the water column or pipe. In general, the longer the pipe line the greater the difficulty.

The opposite condition, that is, a condition requiring the acceleration of the water when, because of a great increase of load, the speed of the water wheels falls far below normal, can be met by installing a small regulation basin or surge reservoir at the end of the conduit (at the forebay). This reservoir serves a dual purpose: (1) It will assist in preventing excessive rise in pressure due to reduction in velocity in the pipe line. (2) It will take care of sudden demands for water or can receive water not demanded by the water wheels. A regulating reservoir or stand-pipe will not afford entire relief due to a sudden closure of the valves, nor do they generally operate in such a way as to make the pipe safe, but in conjunction with a governor-operated by-pass valve or gate (arranged to operate slowly on closing) safety can be had and also good speed regulation. The use of a by-pass valve involves a frequent waste of water equal to that required for the largest load variations, thus, in some plants it cannot very well be permitted. The compromise is to sacrifice part of the speed regulation for the sake of economy of water.

Effective Head of a Development.—The water wheel is a device which is placed in the path of falling water, for the purpose of utilizing the energy possessed by the water, due to its fall and weight, and for delivering as much as possible of this energy to a rotating shaft as mechanical power. The energy possessed by the water may be made to manifest itself as power by: (a) Allowing a quantity to pass from a higher to a lower level practically without velocity. (b) By the momentum possessed by a quantity of it traveling at a velocity caused by the head. (c) By pressure of the water due to head acting on an area through space. That is, the relation between velocity, head and pressure are fundamental, and must always be borne in mind in hydraulic work.

The definition of head (total head) is the difference in elevation between head-water and tail-water. This total head may be divided in general into three different parts, as: friction-head, discharge-head, and effective-head. Friction-head is that part of the total head which is applied in overcoming the friction in the water passages leading to and away from the wheel, as in the passageway through the racks, entrance to pipe-line (inlet of penstock), in the forebay or the penstock itself, through the guides and buckets, and in the discharge tubes, etc. The discharge-head is the head at which the water leaves the draft-tubes and enters the tailrace. The effective-head is that part of the total head left to be applied to the wheel itself after the friction-head and discharge-head have been accounted for.

Characteristics of Water Wheels.—The best known types of water wheels in common use today are the impulse wheels and the turbine. The impulse wheel is a kinetic energy wheel, that is, the momentum of the mass of water in its impact with the runner buckets is the main principle utilized in the energy transformation. The two best known types of impulse wheels are the Girard and the Pelton. In the former the water passes through the runner radically outward, and in the latter, which is the most practical for average installations, the water strikes tangentially upon the buckets. The turbine is a combined potential and kinetic energy wheel, the water passing either inwardly or outwardly through the runner, the wheel rotating partly from velocity action and partly from reaction due to pressure and consequent acceleration in the buckets.

The efficiency of a water wheel will vary considerably with a varying head, since it is designed for a definite head and speed, so that if one is varied without corresponding change in the other, the efficiency is usually materially reduced. Where the load fluctuates heavily and rapidly, there must be ample margin allowed for this character of load, in order that the maximum capacity may not be exceeded, and the average load will then be much below the maximum, with, of necessity, low efficiency. Such fluctuations of load usually accentuate the effect on the units, for they produce corresponding changes in head, due to increasing friction losses in the water conduit and pipe line, etc.

In recent years a rapid evolution has taken place in the design of water wheels, the most marked being the increased application of single-runner, vertical shaft turbines to low-heads, where previously multi-runner turbines of either vertical or horizontal type were used. This has been made possible by the progress of design and development of high capacity runners, so that for a fixed head and capacity it is now possible to operate modern turbines at much higher rotational speeds than was possible with runners of the old design. This increase in power of runners has been obtained without any sacrifice in the maximum efficiency of the wheel and with only a slight sacrifice at partial loads. As the spouting velocity of the water varies directly as the square root of the head, the peripheral velocity of a turbine becomes high in high head installations. The impulse wheel, however, runs at a considerably slower speed than reaction turbines of the same capacity, hence the ease of governing through high kinetic energy of moving parts is not so great as the increased spouting velocity of the water would indicate. Not many years ago the efficiency of the impulse wheel was higher than that of the turbine so that for any development where it could be used to advantage it was chosen where as now the other type has the advantage in both speed and efficiency.

Effective Draft Tubes for Water Wheels.—An important point which is frequently overlooked when calculating the proper head for a given wheel is, the margin allowance between the maximum vacuum and the total draft head. The maximum vacuum should always be considered for the particular elevation above sea level at which the wheel is to be installed. The placing of a wheel within the natural limit (34 ft.) from the elevation of tailrace-water is no indication of the proper elevation, because it is necessary to allow at least 3 ft. to 4 ft. margin between the total draft-head and a perfect vacuum to prevent the breaking of the water column in the draft tube due to inertia effects of sudden changes of load such as those mentioned above.

Not long ago it was generally considered that the draft tube was simply a device to locate the turbine above the tailrace water level without losing the effective head between turbine and tailrace. To-day it is looked upon as an extremely important part of a turbine. In fact without effective draft tubes, runners of high specific speeds would be impracticable. The velocity head of high specific speed runners may be from 25 to 30 per cent. of the total, therefore, it is essential to efficient design for the draft tubes to convert this velocity head into effective head, all of which has been done to a very marked degree. In fact, due to the perfection of draft tubes it is not uncommon to obtain one-third of the total head through vacuum.

Speed Regulation of Water Wheels.—The two greatest difficulties in the operating of water-power plants are the governing of the water column and proper speed regulation, the two being closely related. Today ample governor and compensating devices are to be had, but it should be borne in mind very clearly that even with a perfect governor, speed regulation cannot be any better than that permitted by the length of the water conduit and column and the flywheel effect of the rotating masses. Proper regulation is primarily controlled by the design of the development as a whole, so that actual speed regulation obtained in practice is largely limited, and the use of a governor, no matter how efficient in itself, will have little effect when the other part of the development has been improperly designed.

A good governor with its connected compensating devices will take proper care of any difficulty arising in the water column and will at the same time limit the run-away speed of the water wheel even if the entire load be suddenly thrown off, assuming, of course, proper design of the hydraulic development. A proper compensating device should operate before the rise of pressure takes place in the water column, and no matter how quickly the gate or gates are closed, either by governor, by hand or by accident, there should be no shock on the water column. By a suitable proportioning of the discharge to the discharge of the units, any sudden movement cannot take place in the gate without immediately affecting the velocity of the water in the water column, and consequently without producing the usual surging in pressure (which are one and the same thing), destructive to the water column and good regulation. The action of this device should be absolutely reliable at all times and high in efficiency, that is to say, in water economy. To avoid a great waste of energy when governing proceeds by deflection, wheels have been designed in which the jet of water is not deflected at all, the cross-section of the stream being altered by means of a needle valve in the nozzle. This keeps the efficiency of the wheels high throughout the entire range of output, the only important objection being the element of great danger introduced by sudden variations in the velocity of the water in the water column. However, the best type of impulse wheels are now built by combining deflecting nozzles with needle valves. The governor has control of the deflection, and other means are provided to produce slow movements of the needle valves.

Selection of Water Wheels, Their Rating and Speed.—In low-head installations where it would be practicable to install water wheel units of either type, the single-runner turbine has a number of advantages over the multi-runner. For example, only one gate opening and closing mechanism is required and this is located above the head cover of the turbine and is thus accessible at all times for inspection, while repairs can readily be made to this mechanism without dismantling the wheel. A better design of the draft tube is made possible with a single-runner unit, and it is possible to mould in the concrete a spiral turbine casing similar in design to the cast-iron spiral casings used in connection with high-head turbines, which, of course, would be impracticable with more than one runner.

In the case of a vertical turbine having more than one runner, the depth and consequently the cost of the sub-structure of the power house is necessarily much greater than in the case of a vertical single-runner turbine, and the cost of erection and dismantling for repairs is considerably less in the case of the vertical single-runner wheel.

In deciding upon the number and rating of the units in a station the combination of the water wheel and its generator must necessarily be considered together. Besides hydraulic conditions and the limitations of the water wheel design, the rating is governed by the load factor, the character of the load, the reserve capacity, the reliability and the flexibility of the service, etc. The units should be operated as near full load as possible and new units should preferably be started as the load increases instead of utilizing overload capacities. Where sudden overloads of considerable magnitude come on the system for short periods it is, of course, necessary to have wheel capacity sufficient to care for them. Single units are never desirable except for multi-plant systems, in which case the necessary reserve can be obtained from other stations. For single-plant systems the number of units should preferably not be less than four, but above this the number should be governed by the limit in design, considered both from a technical and economical point of view. With a small number of large units the first cost, the maintenance charge and the necessary floor space are reduced, and the efficiency is also usually better than for a larger number of smaller units.

The generator should have a rated output approximately the same as the most economical rating of the water wheel. The most economical point for the wheel varies for different specific speeds. Even though the revolutions per minute may not be determined and the specific speed not yet calculated, it can at once be said that the maximum horse power of the wheel divided by the kilowatt rating of the generator will vary from 1.5 to 1.9. This is obtained by dividing the maximum horse power by the horse power at the most economical point and then again by 0.746 to secure kilowatt rating. The maximum horse power of a wheel divided by the kilowatt rating of the generator will thus vary from 1.5 to 1.9, depending upon the type of runner that may be selected for use. The matter of overload should always be taken into consideration when this point is being worked out.

The speed of the generator and frequency of the system place some limit on the selection of the speed of the water wheel. It sometimes troubles the wheel manufacturer if he cannot obtain every local hydraulic and electrical condition entering into the case of choice, because many important factors must be considered before a proper wheel design can be made, such as: the head, characteristic efficiency, runner balancing, speed regulation, variation in head, and the durability of design.

The head is the important factor in the selection of the proper speed. Low heads and attendant low velocities permit of a design of bucket to handle large quantities of water. In such a runner, thin warped buckets of ample size and large openings can be used. These buckets are, relatively speaking, structurally weak. High heads and consequent high velocities make necessary a simple design of bucket, thicker material, for relatively small quantities of water. Strength, therefore, must be carefully considered in determining the diameter and speed of a runner. Specific speed varies with revolutions per minute, hence for any given horse power and head the revolutions per minute fix the specific speed, and the characteristic efficiency which is obtained from a runner with the specific speed both for full load and for partial loads. The particular speed characteristic desired, therefore, has much to do with selection of the speed of the runner. A single runner can be designed so as to balance the thrust, which is sometimes desired. With a single runner there is a lower specific speed and, therefore, a consequent large diameter of runner. The question of thrust does not enter into consideration with double runners as the thrust of one runner is neutralized by that of the other. Speed regulation is sometimes the most important item in fixing the speed. The lower the speed the larger are the diameters and weights of the rotating elements and, therefore, the greater the flywheel effect of the units. When the load on a unit is changed the speed varies directly with the flywheel effect. It is therefore often desirable to use a lower speed, fixing the speed by the degree of regulation desired. Extra flywheel effect can be obtained by the use of a flywheel, but this is generally undesirable and if possible should not be considered on account of the danger due to high pressures on bearings.

Variation in head is a common condition in low-head plants. In all hydroelectric developments the speed must be kept constant, even though the head does vary. It has been shown that different speeds have different characteristics of power and efficiency when the runners operate under heads other than those for which they are designed. A lower speed than that given may oftentimes be used to advantage and might mean a considerable increase in the output of the plant. At the same time the initial cost may be greater and in such cases a proper balance between cost and benefits becomes a consideration. In high-head installations particularly, pitting of the runner blades takes place, due to shock of water against the buckets, or high velocity. It is therefore, quite important to consider durability when the unit is working at the most economical point, in making the selection of the proper speed of runners.

Water wheels may have a single runner, a pair of runners, or for low heads, four or even six runners per unit. In some places a vertical design of unit is required, while in others horizontal units best suit the conditions. When a pair of wheels is used, it must be determined whether an outward discharge or a bottom center discharge is the more desirable. The one involves a single draft tube and the other two draft tubes. When low-heads are met with, open flumes are possible and a properly arranged open flume may take the place of the closed flume. In high-heads, of course, it becomes necessary to use closed flumes.

Ten years ago it was a notable achievement to obtain a turbine efficiency of 82 per cent. The maximum guarantees of manufacturers were from 78 per cent. to 80 per cent., and were generally considered highly satisfactory. During the past two years, efficiencies of 89 to 92 per cent. have become quite common, while a maximum value of 93.7 per cent. has been secured, as shown below. Some of the recent large low-head developments equipped with single-runner vertical-shaft turbines, are tabulated herewith:

TABLE 5.—INSTALLATIONS USING SINGLE-RUNNER VERTICAL-SHAFT TURBINES.

NAME	HEAD IN FEET	R. P. M.	CAPACITY IN HP. EACH UNIT	TOTAL
Tallasee Power Company.	180	154	31,000	93,000
Laurentide Co., Ltd.	76	120	20,000	120,000
Alabama Power Company.	68	100	17,500	70,000
Mississippi River Power Company.	32	57.7	10,000	150,000
Cedars Rapids Mfg. & Power Company.	30	55.6	10,000	130,000
Turners Falls Company.	54	97.3	9,700	38,800
Appalachian Power Co.	49	116	6,000*	24,000
" " "	34	97	3,500	10,500
Georgia-Carolina Power Company.	27	75	3,125	15,625

* These turbines showed an efficiency, on test of 93.7%.

The power delivered by a water wheel (friction-brake rating), may be expressed as follows:

$$P=\frac{2\pi lw}{33,000}n$$

where, the resistance overcome by the wheel in a given distance is

$$R=\frac{2\pi lw}{33,000},$$

n being the number of revolutions per minute; *R* being the resistance overcome per revolution; $\pi=3.1416$.

Speed Variations of Water Wheels.—The variations of resistance and speed, and the resulting variations in power (*P*) under various speeds and under certain conditions, are shown in the following curves (Fig. 9). These curves are only illustrative and applicable to a constant speed hydraulic unit when similar series of curves for different nozzle openings are shown. The upper curve shows the relation of resistance to speed at fixed nozzle opening. It would, of course, show different values for various nozzle openings. The lower curve shows the relation of power to speed at the same nozzle opening with corresponding variations to the nozzle openings given in the upper curve.

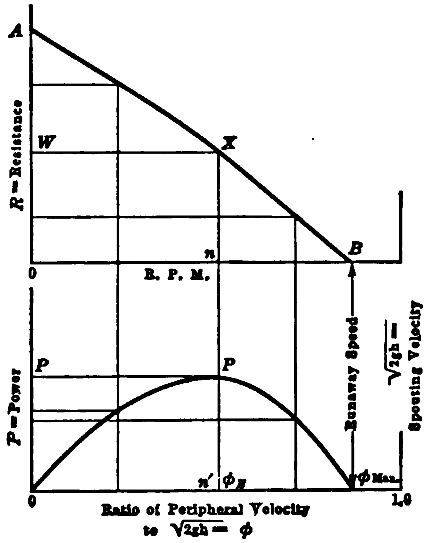


Fig. 9.—Relation of Resistance and Power to Water Wheel Speed

In the lower curve the speed factor is expressed as a ratio between the peripheral velocity of the wheel and the spouting velocity of the water. Under such conditions satisfactory operation will be represented only by various nozzle or gate openings. The point *X* and the corresponding point *P* represents the 100 per cent. nozzle opening of both the upper and lower curves, and consequently the maximum power. If the power varies, as, of course, it does on every system between maximum and zero, satisfactory regulation can only be accomplished by proper change in the nozzle opening as the load varies. The point of position drops below *P* as the power demands decrease, or rises above *P* as the power demands increase. If the load is entirely removed (cut-off) a maximum or runaway speed will result as shown at ϕ_{max}. In practice the runaway speed of a tangential wheel is less than $\phi_{max.}=1.0=\sqrt{2gh}$ on account of nozzle and atmospheric friction.

The maximum speed for which a hydraulic unit should be designed depends to a great extent on the character of the hydroelectric development. Low-head wheels sometimes have a peripheral speed about 70 per cent. of the spouting velocity of the water and may attain 100 per cent. depending on the pitch line used in measuring the peripheral velocity. In high-head plants with a peripheral velocity about 40 per cent. of the spouting velocity, the wheel at 100 per cent. excess speed may still have considerable power. It is generally known that the peripheral speed of a water wheel bears a certain ratio to the spouting velocity of the water on any given head. This ratio as a percentage rarely falls below 40 per cent. and seldom exceeds 80 per cent.

For a given revolutions per minute and head, the horse power output of a runner is proportional to the square of the specific speed. Also for a given head and horse power, the revolution per minute of a turbine or runner is proportional to the specific speed. The specific speed of a runner may be defined as the speed at which any runner would operate if it were reduced to such a size that it would develop one horse power when operating under a head of unity. The numerical value of the specific speed of a runner, expressed in the metric system (in which it remains), may be found by first calculating the speed and power output of the runner under consideration for one meter head, and then mathematically reducing the runner in size until it will deliver one horse power. The speed of this reduced runner when operating at its point of maximum efficiency is its rated specific speed This speed is:

$$N_s = \text{r. p. m.} \times \frac{\sqrt{hp}}{h^{\frac{5}{4}}} \quad \text{(metric system)}$$

$$N_s = 4.46 \times \text{r. p. m.} \frac{\sqrt{hp}}{h^{\frac{5}{4}}} \quad \text{(ft. lb. system).}$$

The value $h^{\frac{5}{4}}$ as a factor for specific speed, N_s, is from the assumption that two wheels of similar design and horse power capacity will have varying speeds on different heads, as

$$h^{\frac{5}{4}} = h^{\frac{1}{2}} \times (h^{\frac{3}{2}})^{\frac{1}{2}} = h \times h^{\frac{1}{4}}$$

Taking N_s as the unit speed, that is, the revolutions per minute of water wheel of similar design developing one horse power on 1 ft. head, then,

$$\text{r. p. m.} = \frac{N_s \times h^{\frac{5}{4}}}{\sqrt{hp}}$$

where h is the head in feet; hp is the horse power of one runner or stream from a nozzle. In other words it can be stated that the speeds of two wheels at the same head will be inversely as the square root of their ratings. (See Chapter VIII for data on specific speeds for impulse and reaction water wheels, Fig. 208.)

In order that a plant may operate continuously at best economy for the load it has to carry, it must be designed to accommodate the characteristics of that load. In making this determination, a careful study should be made of the load-curve and the load-factor, as well as several other important matters. The generator should have a rating approximately the same as the most economical capacity of the water wheel. The most economical point of the wheel varies with different specific speeds. Even though the revolutions per minute may not be determined and the specific speed not yet calculated, the maximum horse power of the wheel divided by the kilowatt rating of the generator as already stated should vary from 1.5 to 1.9.

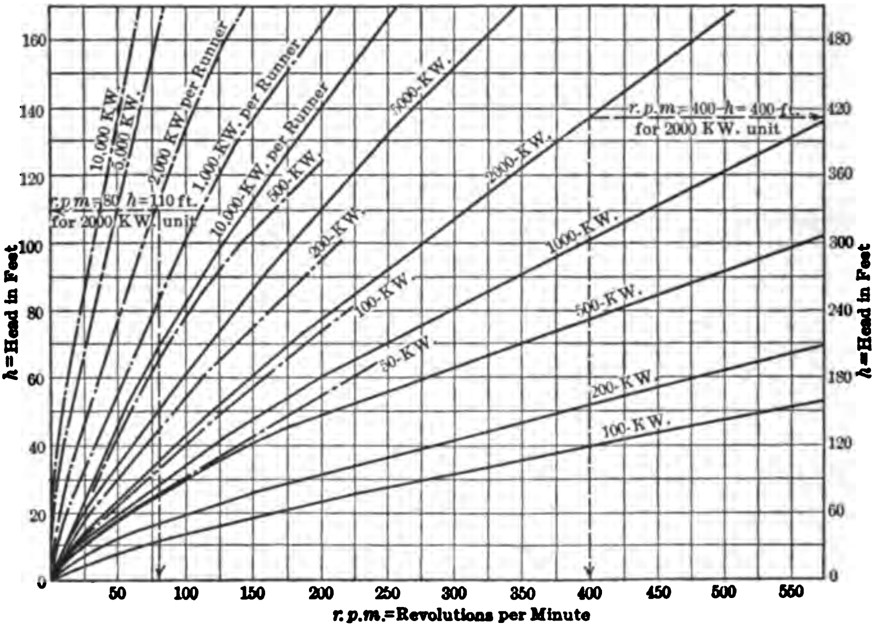


Fig. 10.—Curves Showing Capacity in Kw. per Runner at Various Heads for Low Speed Units of Francis Type

This is obtained by dividing the maximum horse power by the horse power at the most economical point and then again by 0.746 to secure kilowatt rating. It may thus be said that the maximum horse power of the wheel divided by the kilowatt rating of the generator will vary from 1.5 to 1.9, depending upon the type of runner to be used. In the first approximation the value of this coefficient might be taken as 1.75, above the average value, and the kilowatt rating of the generator determined, to be corrected as deemed necessary.

It can be easily shown that the water-wheel horse power varies as $h^{\frac{3}{2}}$ which is fundamental. Equally so is the formulæ $v=c\sqrt{2gh}$, one of the most important of hydraulic formulæ as it enters into all calculations and designs of water wheels. However, a point which should always be kept in mind is, that the speed of hydroelectric plant generators must be kept constant at all times, even though the water wheel head varies.

Take for example a 1,000 hp. plant operating under a 40 ft. head and at 200 r.p.m., and assume the head varies due to floods from 40 ft. to 24 ft., or a change of 40 per cent. in head. It is quite obvious that the generators must operate at their proper and constant speed in order to maintain for the system the proper frequency.

At 24 ft. head the 1,000 hp. wheel will only deliver 465 hp., for

$$\frac{1{,}000}{\left(\frac{40}{24}\right)^{\frac{3}{2}}}=465 \text{ hp.}$$

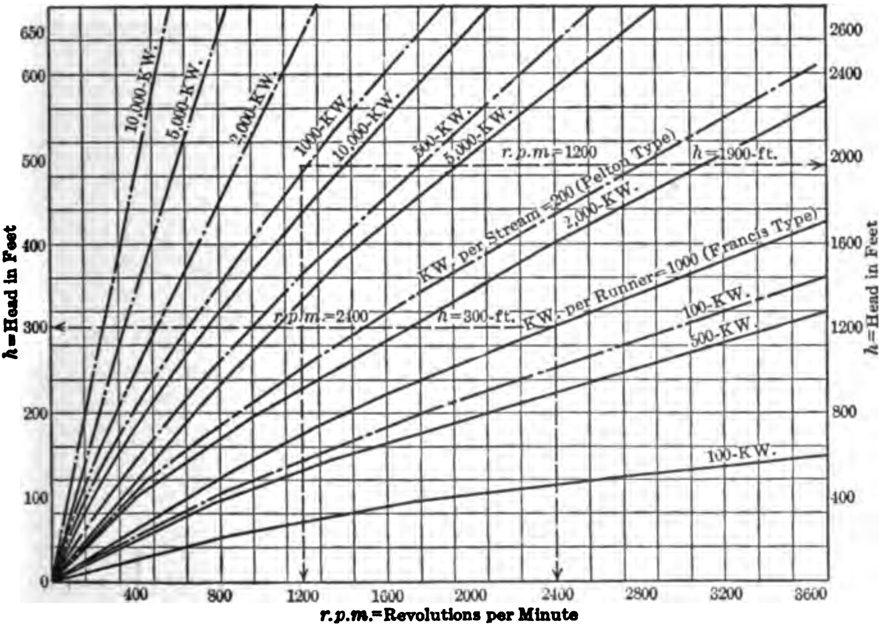


Fig. 11.—Curves Showing Capacity in Kw. per Runner and per Nozzle Stream at Various Heads for High Speed Units of Francis and Pelton Types

This is based on the assumption that the wheel is allowed to run at the proper speed for the 24 ft. head. This speed (since wheel speed varies as $h^{\frac{1}{2}}$) will be 155 r. p. m. for,

$$\frac{200}{\left(\frac{40}{24}\right)^{\frac{1}{2}}}=155 \text{ r. p. m.}$$

This speed, however, cannot be allowed and leaves but one alternative—

that of reducing the rating (power) to meet the nearest speed, which, in the above case, is about 20 per cent. below. In order to increase the speed by this amount, depending on the type of runner, there is nearly a corresponding decrease in power. With the best type of runner it would be a difficult matter to obtain more than 400 hp. from the plant, or, say

$$465 \times 0.125 = 407 \text{ hp. max.}$$

It is interesting to note that, at the present time, single-discharge turbines are in successful operation working under a head of 585 ft., this being the highest head under which turbine wheels have ever run. Of further interest is the fact that the world's highest-head water-power plant is operating under a head of 5,400 ft., or well over a mile of effective head. The penstock lines of this hydroelectric plant are 3 miles long with the upper section built of welded-steel pipes, 24 in. in diameter. The lower section, which will withstand a hydrostatic pressure of nearly 2,500 lb. per sq. inch, or 165 atmospheres, employs special ingot-pressed seamless-steel pipe. The pipe sections vary in thickness from 1.25 in. at the top to 1.78 in. at the region of highest pressure. The full output of this hydroelectric development is 15,000 hp., there being only a maximum of 30 cu. ft. of water per second available.

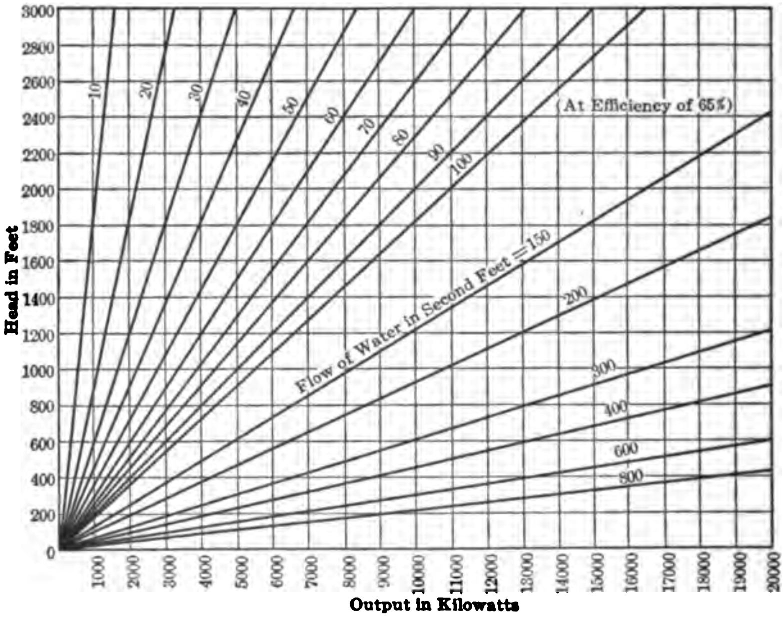


Fig. 12.—Hydroelectric Output in Kw. at Different Heads

Stream-Load Characteristics.—The cost to build a new hydro-electric

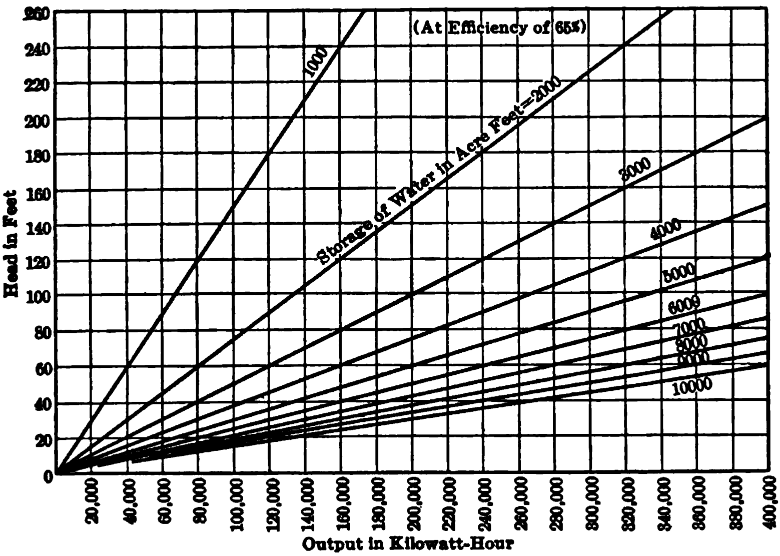


Fig. 13.—Output in Kw.-Hrs. for Given Acre-Feet Storage and Heads up to 200 Ft.

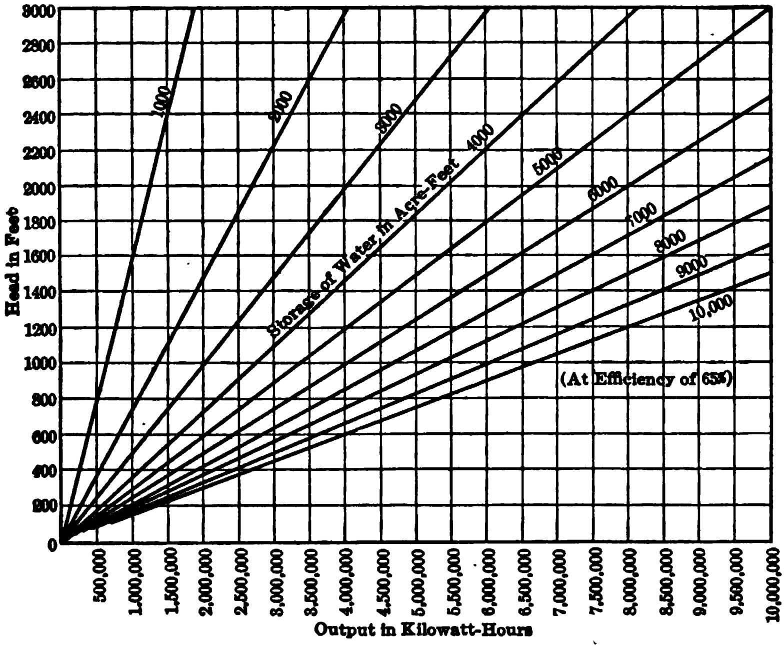


Fig. 14.—Output in Kw.-Hrs. for Given Acre-Feet Storage and Heads above 200 Ft.

project per kilowatt is less as its rating is increased, since a large proportion of the total cost is practically independent of the rating of the equipment. In this case, an increase in the annual cost per kilowatt of an auxiliary plant (steam or otherwise) is accompanied by a decrease in the annual cost of the hydraulic plant, and a point may be reached at which the sum of the two is a minimum. This would fix the most economical rating of the development and hence the point of greatest profit for a given market price of energy. Of course, the plant may be developed for a greater output with a less profit per kilowatt, but the limit to the development is where all profit becomes *nil.* From this it is readily observed that the determination of the cost of the auxiliary supply for the hydraulic characteristics of the stream as applied to the particular conditions of power load prevailing is important.

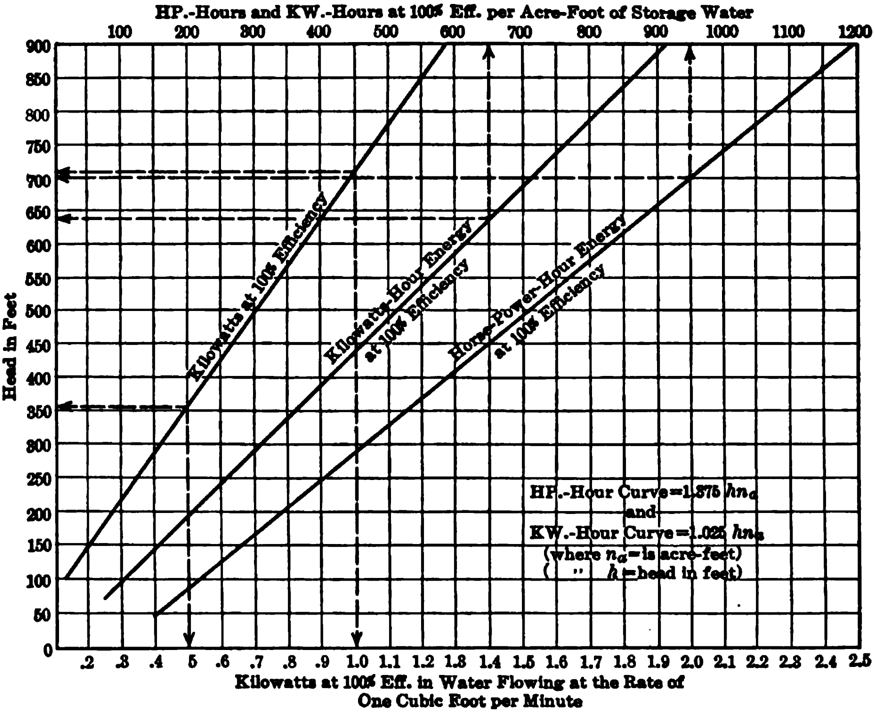


Fig. 15.—Curves Showing Kw. in Water at the Rate of One Cu. Ft. per Min. and Hp.-Hrs. and Kw.-Hrs. per Acre-Foot of Storage Area for Different Heads

As a solution of this problem, one useful method is to apply two curves, one showing the hydraulic characteristics of the stream called the "per cent. deficiency" curve, and the other characteristics of the load called the "per cent. load" curve. The use of these two curves, the one summarizing

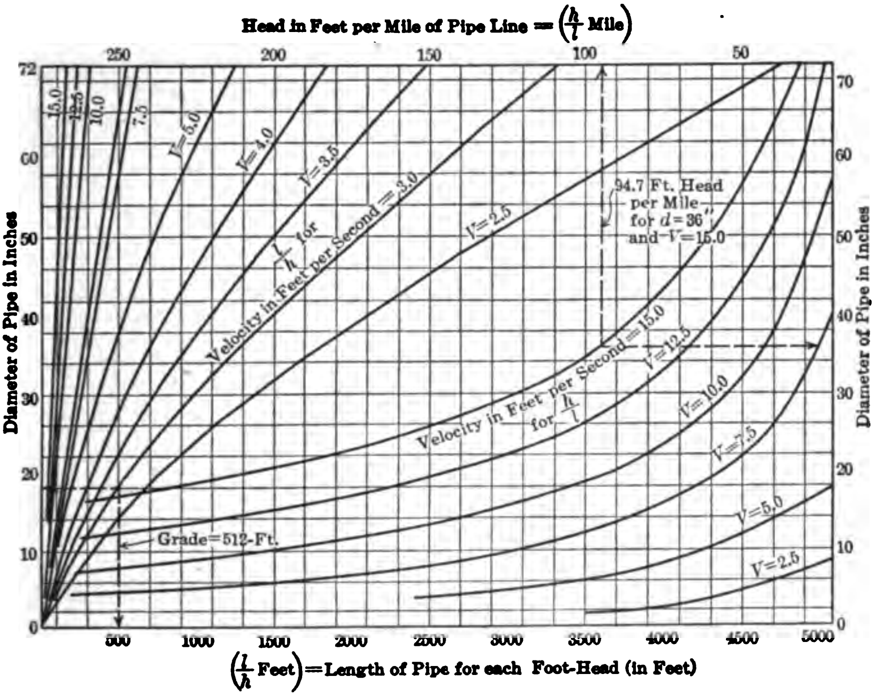


Fig. 16.—Head in Ft. per Mile of Pipe Line and Length of Pipe Line for Each Ft. Increase in Head with Different Velocities and Diameters of Pipe

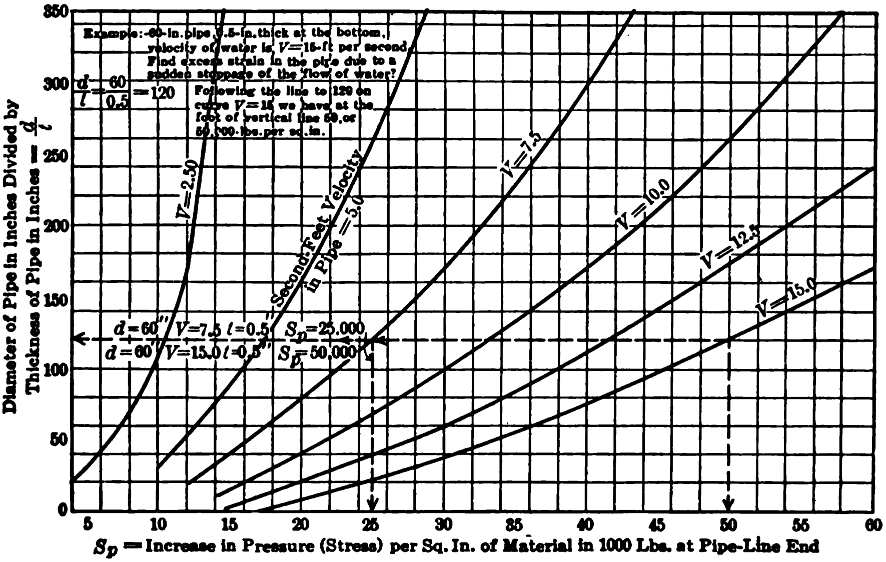
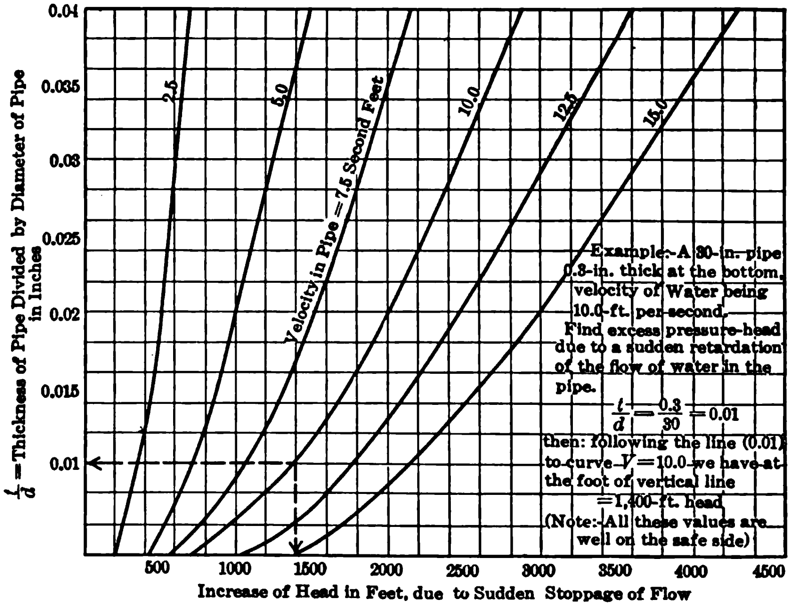


Fig. 17.—Curves from Which the Excess Strain in Pipes Due to Sudden Stopping of Flow can be Found when *d. t,* and *V* are Known

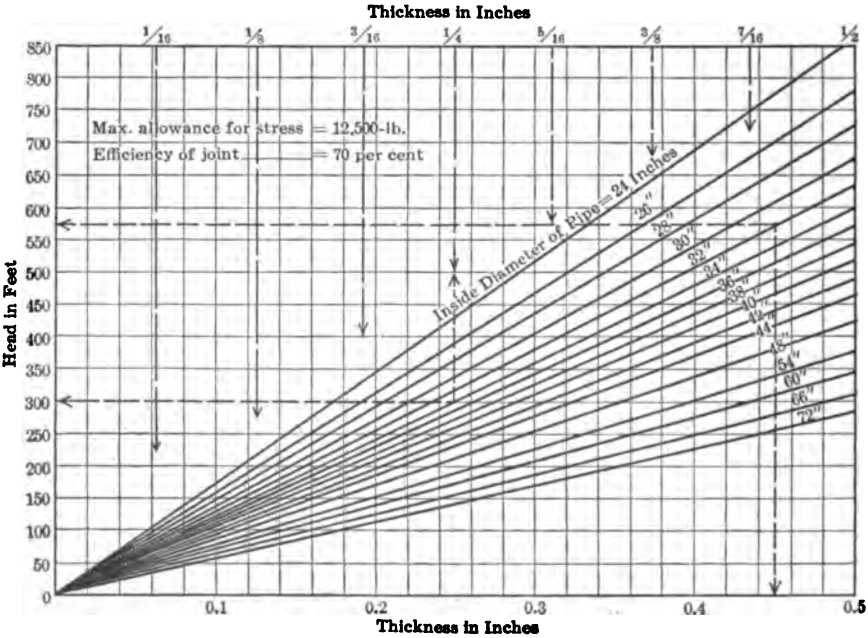


Example:-A 30-in. pipe 0.3-in. thick at the bottom, velocity of Water being 10.0-ft. per second.
Find excess pressure-head due to a sudden retardation of the flow of water in the pipe.

$$\frac{t}{d} = \frac{0.3}{30} = 0.01$$

then: following the line (0.01) to curve $V = 10.0$ we have at the foot of vertical line $= 1{,}400$-ft. head
(Note:-All these values are well on the safe side)

Fig. 18.—Curves Showing the Excess Pressure-Head in Feet Due to Sudden Stoppage of the Flow of Water in a Pipe Line



Max. allowance for stress = 12,500-lb.
Efficiency of joint = 70 per cent

Fig. 19.—Thickness of Steel Pipe Required for Various Diameters and Heads

the stream-flow data, the other the conditions of the load, make the determination of the total cost of an auxiliary supply for any conditions of load and any particular stream quite simple. The "per cent. deficiency" curve is the most convenient form for the use of stream-flow data, for by assigning suitable values to the efficiency, the "deficiency" can be referred to any part of the entire system, as, to the wheel-shaft, to the power-house busbars, to the sub-station busbars or to any other part of a hydroelectric system. The energy to be supplied to the auxiliary plant is deduced directly from this curve by using the suitable efficiency. For example, assume the efficiency from the water to the sub-station buses to be 65 per cent., then from a stream flow of 0.5 sec. ft. and a head of 60 ft. the power at the sub-station buses will be approximately 1.65 kw.

The deficiency in stream-flow is approximately expressed as

$$K=100\left(\frac{q-q'}{2}\right)\left(\frac{D}{365q}\right) \text{ in per cent. value}$$

where

q = represents any stream flow.
q' = the minimum stream flow.
D = the number of days deficient (following the approximate equation $0.08+D/220$).

This per cent. deficiency fixes the increased cost per kw. hour of the total combined hydraulic and auxiliary supply, for plants with storage capacity, when the total cost per kw. hour of the auxiliary supply is a constant amount. It also determines one of the principal factors that fixes the economical size of the auxiliary plant. The expression: $(0.08+D/220)$ means that any fixed increase or decrease in the flow will take place in the same number of days. As the stream-flow is directly proportional to power, this means that the number of days used is the same at all parts of the per cent. load curve.

CHAPTER II

LOW, MEDIUM AND HIGH HEAD DEVELOPMENTS

When complete hydraulic information and data concerning a water-power development have been compiled the design of the hydroelectric end begins with a consideration of the proper number of generators and turbines, transformers and outgoing lines to supply the demands of the prospective load. Before deciding on these points the methods of operating the system as a whole should be well worked out. The general layout should always be considered the all-important factor, and must consider the capacities of the different generators, prime movers, the generating stations themselves, the water conditions, the characteristics of the load, and the like. The problems of operation divide themselves into normal operation and emergency operation.

The normal problems of operation include such factors as starting up a system, paralleling the generators and the power stations and properly dividing the load among them, of putting units into service previous to the demands of the load conditions, of regulating the voltage for the proper distributing points, of connecting the high-tension lines, and, in general, of so manipulating the generating, transforming and switching apparatus as to deliver the desired load at the distributing centers, with the desired characteristics. These problems are met only after careful study of all the conditions involved, and by so laying out the power station system of connections, the apparatus and the transmission lines as to accomplish the desired object with the best efficiency. All these factors will be readily observed by considering the practical features that have been worked out for the large number of important hydroelectric stations and systems that are described in the following pages.

Economy of Construction.—In the design and construction of a great many existing hydroelectric plants a far too liberal consideration to extravagance is apparent and equally so is the absence of proper consideration for operating economy. Of late, however, a great deal of attention has been devoted to the possibility of reducing the investment outlay and the fixed charges for substations, particularly for small substations. This has brought about a rapid development in out-of-door designs, especially those at which the operator may be dispensed with. With the very high voltage systems and the consequent necessity for greater clearance and spacings of conductors, the saving in outdoor substation installations becomes considerable, and the limit regarding their use has not as yet by any means been determined. Even in sections where severe winter climate is experienced, the small outdoor substation with oil-insulated transformers has worked satisfactorily, the only difficulty being in the case of repairs. In such cases where winter conditions are severe, auxiliary heating apparatus may be placed in the transformers and switches and an oil may be used which freezes at extremely low temperatures. In general, it is a matter of good judgment when deciding on outdoor installations to properly consider the saving in cost and the extra risk involved, especially in the large high-voltage installations.

Transformer Station Connections.—The receiving station system connections may be either star-delta, delta-delta or star-star. The most flexible system of connections is to connect high-voltage apparatus in the same way at all important generating and receiving stations. The star-connection (star on the high-voltage side) with the neutral point grounded either at the generating station only or at both the generating stations and at the substations is usually advisable. The grounding may be solid or through non-inductive resistors, this being settled by local conditions and personal opinion. The connection for the low-voltage side most prefered is delta isolated. To connect a delta-delta system of supply with a delta-star (star on high-voltage or primary side) is poor practice, for the reason that a ground on one line connecting the delta source of supply with the grounded star-connected system will impress 173 per cent. of normal voltage across the high-voltage windings of two of the transformers in the group of three single-phase units or the two windings of a polyphase unit of the star-connected system, with the result that great damage due to the higher voltage might be done to apparatus, etc., connected on the secondary side.

It is of the greatest importance that the testing of the whole of the main plant in a power station as well as in a substation be carried out at certain periods and that the results obtained be absolutely reliable and be available for the operators in their respective stations as reference. In very large power stations suitable men can generally be found to properly carry out these duties as well as their ordinary duties, but such men are not always to be found in the smaller stations. The most important point is the overall efficiency (hydroelectric efficiency) and these tests help to make it the highest if they are only executed with the aim of having the most economical plant (hydroelectric plant) and bring to the attention of all concerned the capital outlay per kw., cost of operation and the cost of production, etc.

Generating Costs.—The cost of manufacturing electrical energy is quite variable and depends mainly upon the cost and conditions of the development. In the larger and more modern systems it ranges from a few mills per kilowatt hour for power developed in large quantities to a few cents.

A very interesting and accurate table of costs given by the United States Reclamation Service for the year 1913 follows.

TABLE 6.—COST OF MANUFACTURING ELECTRICAL ENERGY IN HYDROELECTRIC STATIONS

System	Capacity Kw.	Annual Load-factor in Per Cent.	Output in Kw. Hr.	Cost in Cents Per Kw. Hr.
(a) Minidoka Project	7,000	46.1	28,265,287	0.126
(b) Truckee-Carson	1,250	8.5	930,360	1.118
(c) Strawberry Valley	850	11.6	861,705	2.572
(d) Salt River Project	8,560	12.7	9,518,570	0.810
(e) Boise Project	1,875	43.2	7,082,123	0.268

NOTE.—The cost given for plant (c) is high because it includes heavy canal charges. All the costs are at the power plant switchboards and include, in addition to all maintenance and operating charges, general charges and plant depreciation.

The major portion of the cost of a complete development is usually in the hydraulic end rather than in the electric end. In fact, the electric end rarely exceeds 20 per cent. of the hydraulic cost and in some large plants of medium cost per kw. it is as low as 10 per cent. For given conditions the cost of the electric equipment can usually be closely estimated. The cost of the hydraulic work, the most important factor of the total investment, is likewise the most difficult to estimate within any degree of accuracy. The total investment per kw. developed usually ranges between $200 to $300. This figure is high compared with the cost of large steam-turbine plants, but the latter have in general much higher maintenance and operating expenses, etc.

I. HYDROELECTRIC STATION AT KEOKUK, IOWA, ON MISSISSIPPI RIVER

Features of Development.—Besides a huge power-house, 900 ft. long and 133 ft. wide, and a dam 50 ft. high and nearly a mile long, the great project at Keokuk, Iowa, includes for the benefit of river navigation the creation of a lake 65 sq. miles in area, in place of the former tedious rapids and canal; a navigation lock 400 ft. by 110 ft. with a 40 ft. lift,—as wide and high as those at the Panama Canal,—a dry dock, 150 ft. by 463 ft., and a river-crossing bridge 30 ft. wide, carried on the piers of the dam structure. Although there are other water-power plants whose future extensions will bring them within the range of its horse-power capacity, these are chiefly high-head installations whose physical scale can hardly be compared with the huge hydraulic structures necessary to produce 300,000 hp. from the 32 ft. head available. The dam, power house, locks and sea wall constitute one huge monolith of concrete. The scale of this development and the relatively low potential of the water-power available have resulted in some interesting departures in plant design.

This station is among the first to employ low-speed generators directly connected to single-runner turbines. The spiral turbine chambers are unique, being cast directly in the monolithic concrete of the substructure, without the usual steel linings employed elsewhere. The method of turbine setting was necessarily unusual to withstand the tremendous weights which have to be supported, for each 10,000 hp. hydraulic unit weighs 1,000,000 lbs., exclusive of the alternator. Also, the demand for excitation energy was so great that it was found desirable to generate this energy as alternating current by auxiliary 2,000 hp. water wheel sets. In such form it is distributed to various individual motor-driven exciter generators ranging along the 900 ft. power-house gallery, each opposite its own main unit. The main alternators are regulated by adjusting the fields of their individual exciters, in this way eliminating large field rheostats and energy losses.

Dam.—The 4,649 ft. dam is a huge concrete monolith, 4,278 ft. in length, not including the east and west abutments, which measure 290 ft. and 81 ft. respectively. It is made up of 119 arched spans, each having 6 ft. piers and 30 ft. openings. Each opening contains a concrete spillway section, on top of which is set a 11 ft. by 32 ft. sliding steel gate for controlling the discharge volume through that section. These gates are handled electrically by cranes traveling on the top of the viaduct. The dam structure is 52 ft. high, 29 ft. wide at the top and 42 ft. at the bottom. Its base is set on, and keyed for a depth of 5 ft. into the river bedrock of blue limestone.

This dam is of the gravity-section type, resisting the pressure of the water by its own weight. The up-stream side of the spillway sections is vertical, the down-stream side being rounded off into an ogee curve, discharging the flow quietly into the river below. Sliding steel gates have their edges milled to make a water-tight joint with the iron sill-plates against which they fit. Approach piers have been erected to join the dam viaduct with shore roadways, so that the dam will serve the local community as a splendid river crossing and railroad bridge.

Extending in a gentle curve from the up-stream corner of the power house is the concrete ice fender which will guard the plant forebay. Of its total length (2,625 ft.), 2,325 ft. are made up of concrete construction carried on 10 ft. piers, while the remaining 300 ft. are formed by a floating boom of timber. The concrete section comprises twenty-nine 60 ft. spans, the top of the structure rising 5 ft. above high water, while the openings are submerged 4 ft. below the low-water level. The fender is 8 ft. wide at the top and 16 ft. across at the base. Retaining walls, lock, power-house structure and dam are all tied together as a single monolith of concrete whose length, 10,560 ft., or 2 miles, measured from end to end, is believed to make it the longest monolith of its kind.

Power-house.—The concrete substructure for the entire 30-unit power-house, 1,718 ft. long and 133 ft. wide, is completed, although not entirely equipped. The substructure is 70 ft. high, measured to the generating-room floor, while the superstructure adds 107 ft. additional, taken from

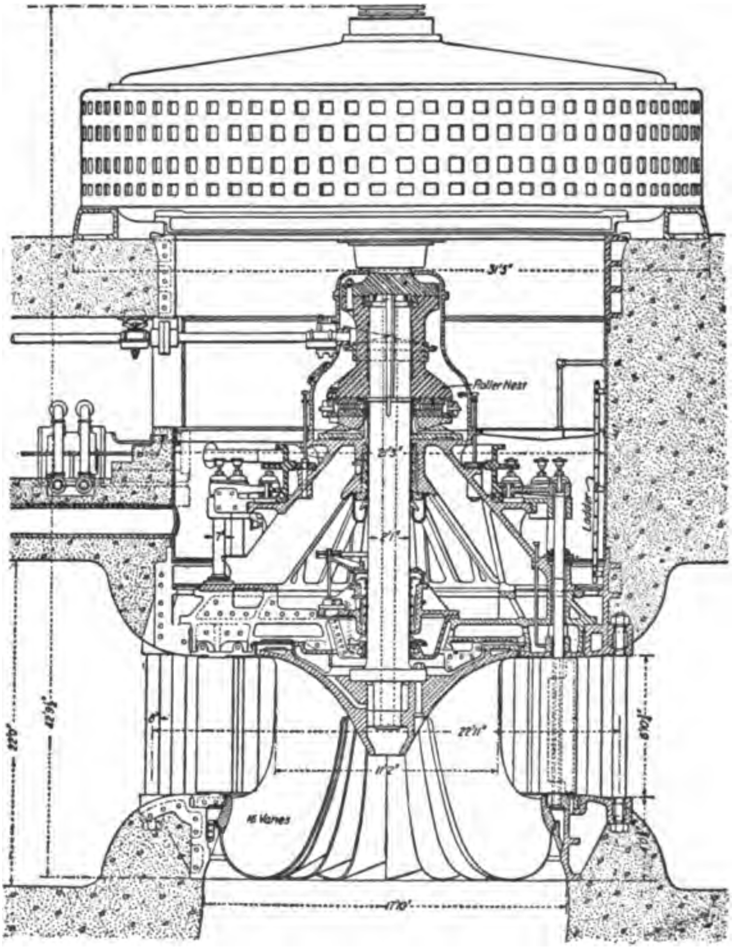


Fig. 20a.—Section through Turbine Unit in Keokuk Station of Mississippi River Power Company

This is the largest low head hydroelectric plant yet built. The station layout provides for thirty units each comprising a 10,000 hp. special single runner vertical Francis turbine connected to a vertical 9000 kva. 11,000 volt, 25 cycle, three-phase generator operated at 57.7 r. p. m. The turbines which operate on a head varying from 29 ft. to 43 ft. were furnished by I. P. Morris Company and the generators and electrical equipment by General Electric Company. Hugh L. Cooper was chief engineer in charge of hydroelectric design and construction of dam, power-house and locks. The station superstructure, electrical equipment and transmission lines were designed by Stone and Webster Engineering Corporation, Boston, Mass.—*Electrical World*, May 31, 1913.

generator floor to roof. For the substructure foundations excavation was carried 25 ft. below the surface of the blue limestone bed of the river. From the forebay the water passes through the racks and gate openings in the gatehouse section of the building, thence entering four branch intake tubes for each 10,000 hp. turbine. These four entry openings each measure 22 ft. by 7 ft. 6 ft. in section. Three are branch tubes opening into a common passage which delivers water to the scroll chamber at the sides and rear of the turbine setting. The fourth is self-contained up to the guide vanes, and supplies the front section of the wheel. By the design of the scroll chamber, 39 ft. in diameter, and moulded to follow the mathematical curvature required, the water is impinged upon the turbine blades from all sides with equal force and velocity.

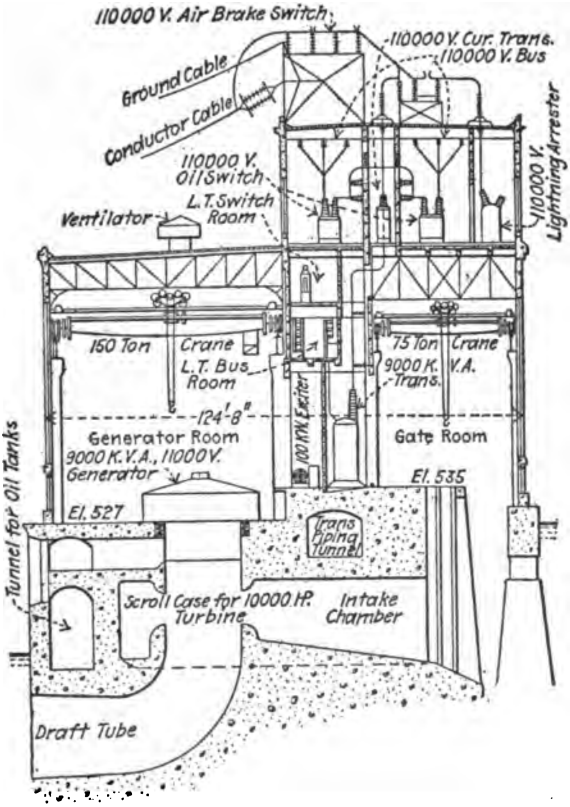


Fig. 20b.—Section through Turbine Setting and Switching Apparatus in Keokuk Station of Mississippi River Power Company

Draft Tubes.—The draft tubes leave the bucket wheels as circular discharge openings having a diameter of 18 ft., but rapidly enlarge in section as the tubes assume a horizontal direction to empty into the tailrace. At the final point of discharge the velocity is about 4 ft. per second, or less than 3 miles per hour, assuring quiet entry into the tail-pool. At the top of the draft tube, in the constricted cross-section, however, the water is required to move with a speed of 14 ft. per second, or 9 miles per hour The tailrace openings from the draft tubes measure 22 ft. 8 in. by 40 ft. 2 in., being made up in sections by two semicircles joined by straight lines at top and bottom. The lower edge of these openings, as well as the bottom of the tailrace, is 25 ft. below the bed of the river. The tailrace is excavated to this depth for a distance of half a mile down-stream.

Single Runner Turbines.—Each of the main 10,000 hp. turbine units consists of a single 15 ft. runner equipped with balanced guide vanes con-

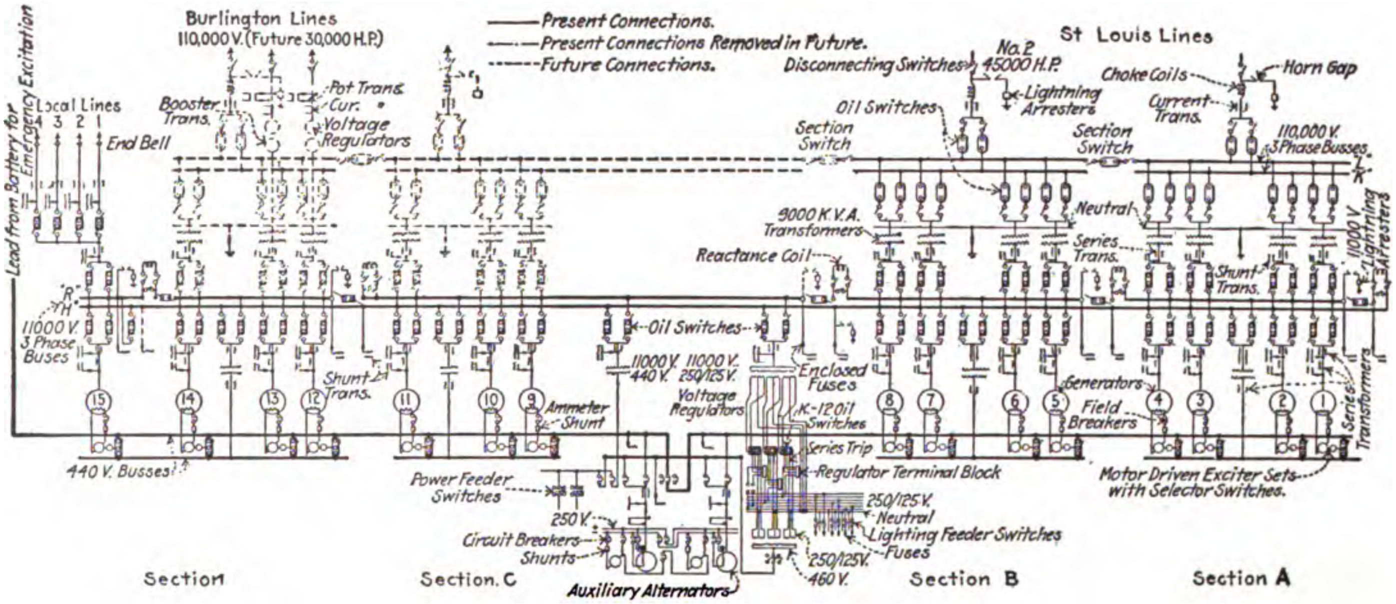


Fig. 21.—Layout of Apparatus and Circuits in Keokuk Generating Station

trolled, through exposed operating mechanism, by a governor on the main generator-room floor. The main turbine shafts are 25 in. in diameter and 21 ft. long. With the rotary alternator field in place, the total revolving weight carried is 225 tons. This is carried by a thrust bearing and by two main-shaft bearings. On the first 10,000 hp. machines installed the standard combination roller and oil-pressure bearing employed utilized oil at 225 lb. pressure, which normally keeps the 225 ton load lifted off the rollers. In case of failure of the oil-pressure, of course, the load is transferred to the roller bearings. Oil is supplied by gravity to the upper bearings, being thence drained to the reservoir under the lower bearings, from which it is pumped to central supply tanks. The type of thrust bearing used requires oil circulation at only atmospheric pressure and introduces a low degree of friction. Each main runner carries 20 buckets and weighs 65 tons, while the complete turbines weigh approximately 1,000,000 lbs., or 500 tons.

Conditions of high and low water level cause varying operating heads ranging from 39 ft. maximum to 20 ft. minimum. For the average normal head obtained of 32 ft., the turbines are rated at 10,000 hp. At 39 ft., however, each unit will develop 14,000 hp., and at 20 ft., 6,000 hp. This low head condition was a factor in the selection of a turbine speed of 57.7 r. p. m. At times of low head it becomes of the greatest importance to get all possible rating out of the machines at 57.7 r. p. m.

Generators.—The initial installation called for fifteen main generating units, each 9,000 kva., 11,000 volts, 25 cycle, three-phase vertical alternators, having their rotating fields carried on the water wheel shafts and running at 57.7 r. p. m. These machines measure 31 ft. 5 in. in outside diameter. In height they extend 11 ft. 3 in. above the generator-room floor, the field collector rings being reached by platforms extending from the side-gallery level. In addition to these main units there is a pair of 1,600 kw. auxiliary alternator sets whose special function is to furnish 440 volt, 25 cycle energy to operate the individual motor-generator units by which the main generators are excited. These auxiliary alternators are of the same direct-connected vertical type and are driven at 125 r. p. m. Each has its own direct-current exciter mounted on the shaft extension above the alternator, so that the auxiliary alternators can be started up as self-contained units.

The exciter motor-generator sets can also be driven with 440 volt, 25 cycle energy taken from the main 11,000 volt bus through transformers provided for the purpose, thus giving an alternative source of excitation energy, besides the special auxiliary alternators. In case of emergency, connections can also be established with one of the duplicate 320 amp. hr. storage batteries used for operating the oil switches. Parallel operation of all the voltage regulators controlling the exciter fields of the various main alternators is accomplished with the aid of series transformers inserted in the machine leads, so that the exchange currents between units are automatically compensated for.

Transformers.—At the gatehouse section of the building in a separate

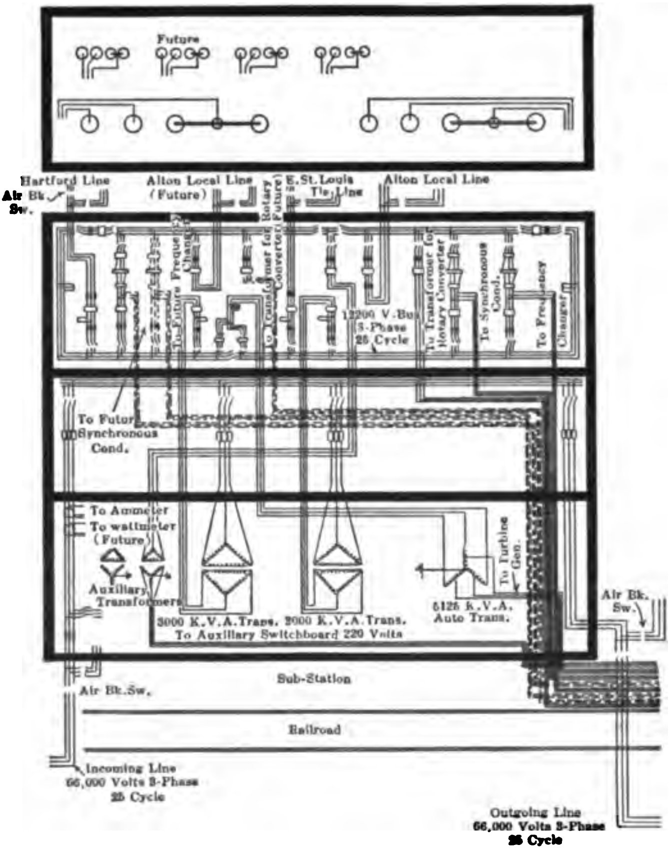

Future
Hartford Line
Air Bk. Sw.
Alton Local Line (Future)
To Transformer for Rotary Converter (Future)
E. St. Louis Tie Line
Alton Local Line
To Future Frequency Changer
12200 V. Bus 3-Phase 25 Cycle
To Transformer for Rotary Converter
To Synchronous Cond.
To Frequency Changer
To Future Synchronous Cond.
To Ammeter
To wattmeter (Future)
Auxiliary Transformers
3000 K.V.A. Trans.
3000 K.V.A. Trans.
To Auxiliary Switchboard 220 Volts
To Turbine Gen.
3125 K.V.A. Auto Trans.
Air Bk. Sw.
Sub-Station
Air Bk. Sw.
Railroad
Incoming Line 66,000 Volts 3-Phase 25 Cycle
Outgoing Line 66,000 Volts 3-Phase 25 Cycle

Fig. 22.—Water Power Substation at Alton, Ill., Tied in with Plant at Keokuk, Iowa

This substation receives energy from the 66,000 volt lines of the Mississippi River Power Company. Incoming and outgoing 66,000 volt lines and outgoing 13,200 volt lines terminate in this substation. Outgoing 66,000 volt lines are carried on steel towers to a substation at East St. Louis. The lines are brought through the Alton substation so that all 66,000 volt energy received from the Mississippi River Power Company can be measured. Two 13,200 volt lines at 25 cycle connect the Alton substation with the East St. Louis station while two 13,200 25-cycle lines leaving this station connect with local points. The Alton substation is divided into three rooms, a transformer room, 66,000 volt switch room and 13,200 volt switch room. Lightning arresters for both incoming and outgoing 66,000 and outgoing 13,200 volt lines are installed on the balcony above the 13,200 volt switches. Two three-phase, 25 cycle 3000 kva. transformers, a three-phase 25 cycle 3125 kva. auto-transformer and two 13,200/220 to 125 transformers for 66,000 volt metering comprise the apparatus in the substation. In the 66,000 volt switch-room a 66,000 volt oil switch connects an incoming line with 66,000 volt bus while one 66,000 volt oil switch connects this bus to 66,000 volt outgoing line to East St. Louis and a 66,000 volt oil switch is provided for each of the two 3000 kva. transformers. By dividing the ring bus into four sections, two on each side of the room and supporting these in concrete compartments quite a saving in space was possible.—*Electrical World*, August 15, 1914.

concrete cell opposite each main alternator is grouped its corresponding 9,000 kva., three-phase transformer unit, stepping up from the generator

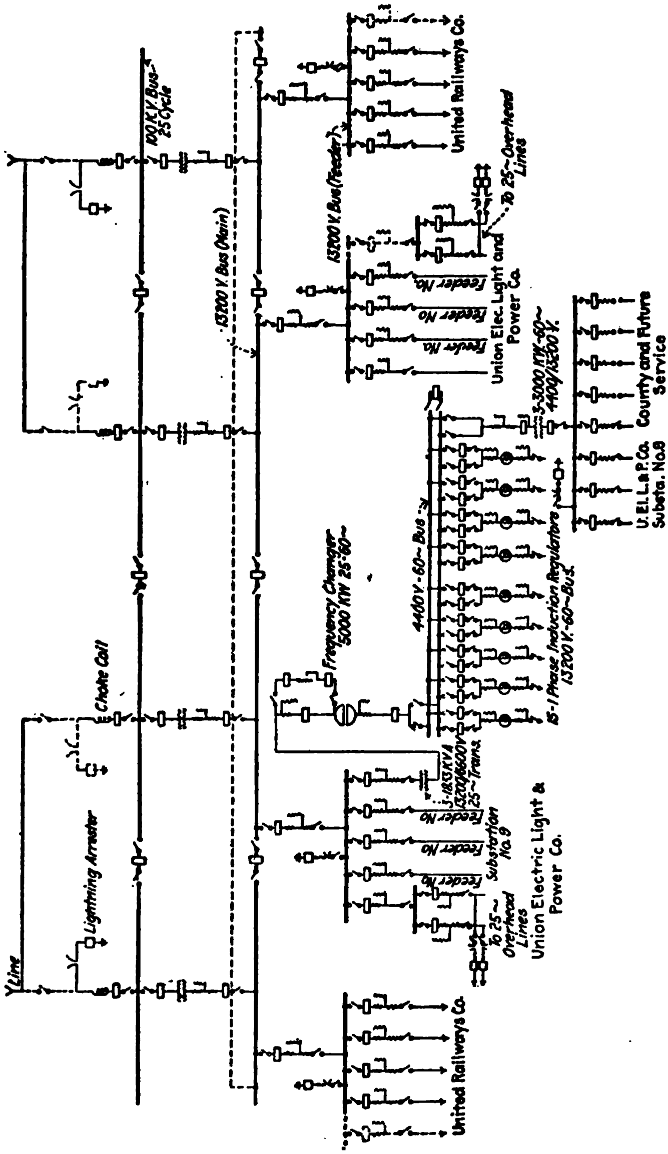


Fig. 23.—Layout of East St. Louis Substation Which Receives Energy from the Keokuk Generating Station

pressure of 11,000 volts, to the transmission potential of 110,000 volts. These transformers are connected delta low-tension and star high-tension with the neutral lead grounded. Their boiler-steel cases measure 16 ft.

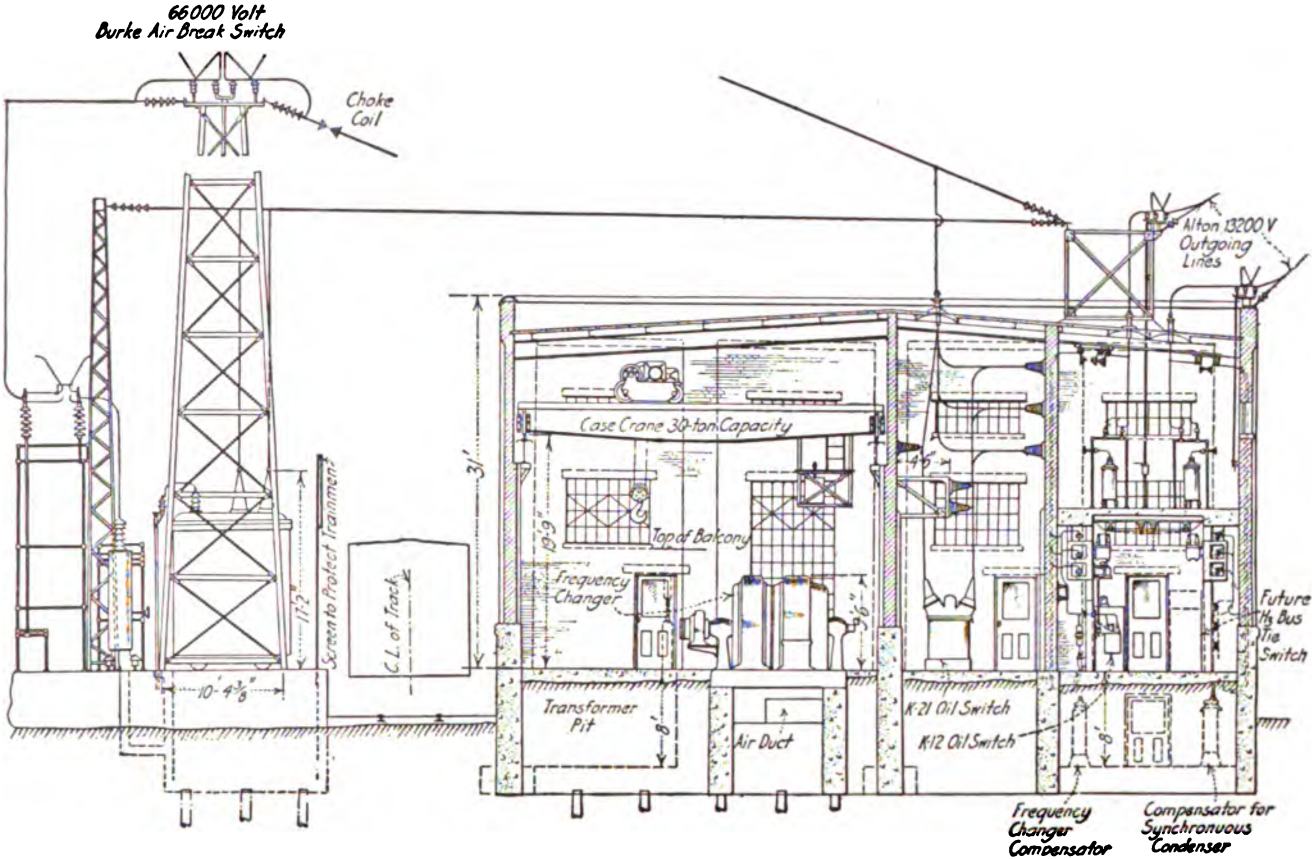


Fig. 24.—Section Through Substation at East St. Louis Showing Arrangement of Equipment, Incoming and Outgoing Lines

This station receives energy from the Keokuk, Iowa, hydroelectric station for distribution. It has a rating of 10,000 kva. and occupies a space 61 ft. wide by 105 ft. long by 31 ft. high. The energy is received at 66,000 volts and at 13,200 volts 25 cycles and distributed through 13,200 volt 25 cycle, 2300 volt 60 cycle, and 600 volt direct current feeders.—*Electrical World*, October 9. 1915.

by 8 ft. in plan and were shipped in two sections, to be riveted together on the job. They measure over all nearly 25 ft. from the floor to the top of the compound-filled porcelain-and-fiber bushings. The units are mounted on rollers and can be run out from their cells under the traveling cranes of the gatehouse for removal or dismantling. Each of these transformers, complete with core and oil, weighs 123 tons. The efficiency rating of these 9,000 kva. transformers is 98.5 per cent., although on account of their great size the dissipation of the remaining 1.5 per cent. as heat requires 56 gal. of cooling water per minute. Each unit contains about 10,000 gallons of oil.

Pipe connections to the bottom of the transformer cases permit filling or emptying the tanks while in position. The 4 in. supply line for admitting oil is controlled by a gate valve whose hand wheel is enclosed in a glass-covered box in the generator room. Similarly, the quick-opening valve in the 6 in. discharge line is also extended through the wall to a hand-lever which can be easily reached in emergency, for dumping the oil contents of the transformer into the tailrace if made necessary by fire peril. There are duplicate pipe systems of circulating water for cooling the transformers, the valves and visible discharge nozzles of each unit being mounted on the generator-room side of the wall opposite its cell and under the direct supervision of the generator-room operators. While each alternator is closely grouped with its 9,000 kva. transformer, both in its position and its operation, connection of the two is actually established through means of the duplicate 11,000 volt buses, to which motor-operated oil switches connect both generators and transformers.

II. High Falls Development on Peshtigo River in Northern Wisconsin

The dam shown in Fig. 25 is on a rock ledge. At the foot of this ledge, with its north wall 65 ft. from the penstock entries, is the generating station, containing at the present time five 1,000 kw. turbine-generators. Water is conducted to the turbine wheels through $\frac{3}{8}$ in. boiler-steel conduits, 8 ft. in diameter and 80 ft. in length. At their upper ends the penstock entries are protected by trash gates and by double vertical lift-gates, raised through racks by movable gate hoist driven by a 7.5 hp. motor. Each entry chamber is provided with a small hand-operated filler gate, for filling the penstock, and with a 10 in. air vent, through which is also brought out the chain controlling the valve to the drain that cleans the penstock chamber of leakage water. The penstocks for the exciter turbines are 3 ft. in diameter.

This dam at its 85 ft. level creates a series of three lakes extending back eight miles having a total area of 1,670 acres. This represents a storage of about 859,805,000 cu. ft., or the equivalent of 1,375,000 kw. hrs., allowing for

80 per cent. efficiency of the water turbines. At the 75 ft. level 840 acres are impounded, storing 174,000,000 cu. ft., or the equivalent of 246,000 kw. hours. The possession of this large storage capacity enables the total monthly flow of the stream to be conserved and utilized as the load demands it. Thus, while the minimum daily flow of the river is equivalent to only 1,200 kw. through 24 hours, it becomes possible with the aid of the storage of water to develop 7,000 kw. under the average load factors equivalent to 10 hours' daily use of this demand.

Generating Units.—The main generating units comprise five 1,900 hp. horizontal shaft twin-runner, plate-case water wheels driving 1,000 kw. 2,300 volt, 25 cycle, three-phase alternators at 375 r. p. m. These units are individually controlled by oil governors equipped with several improved features for securing steadiness of action. On account of the long penstocks and the comparatively light rotating parts of the units it is necessary to change the admission-gate settings comparatively slowly, so that use is made of flywheels on the turbine shafts to overcome momentary changes of load. These flywheels are solid cast-steel disks with heavy hubs 7 ft. 10 in. in diameter, and have a moment of inertia of 80,000 ft.^{2}lb. The turbines are designed to operate under a maximum effective head of 80 ft., but show sustained high efficiency under heads down to 65 ft. and at partial and full loads. The exciter sets comprise two 375 hp. horizontal shaft, single-runner, spiral-case turbines, driving 200 kw., 120 volts, D. C. generators at 500 r. p. m. The output of either set is sufficient for the excitation of the entire plant. Discharge water from the turbines is con-

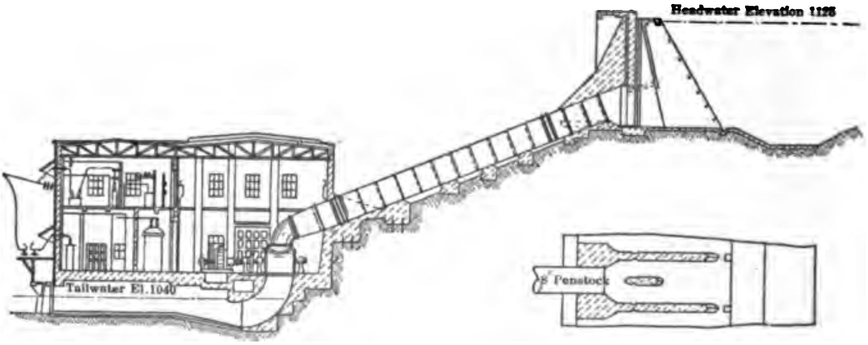


Fig. 25.—High Falls Development of the Wisconsin Public Service Company on Peshtigo River

The station at High Falls was built by the Northern Hydroelectric Power Company in 1910 and is operated in connection with a transmission system in Northern Wisconsin. The generating units comprise five 1900 hp. horizontal shaft twin-runner plate case water wheels driving 1000 kw. 2300 volt, 25 cycle, three-phase alternators at 375 r. p. m. The water wheels operate under a head varying from 65 to 80 ft. The water wheels, alternators, exciters and governors are of Allis-Chalmers design. This development was designed by Prof. D. W. Mead as consulting engineer and the construction supervised by W. Reineking as resident engineer.—*Electrical World*, November 24, 1910.

ducted through draft tubes, moulded in the generating station concrete foundations, under the generating room and out into the tailrace.

Power Station.—The power station is a two-story concrete structure, 136 ft. by 83 ft. in plan, the second floor forming a gallery for the installation of switches, etc. The flat-tile roof is supported by steel truss construction 38 ft. above the generating room floor. Directly beneath it is the runway for a 30 ton hand-operated crane. Besides the generating units on the first floor are installed the step-up transformers, the 66,000 lightnings arresters, the 66,000 volt tie-switches, the transformer oil-treating outfit, and a machine shop.

On the gallery level are the main switchboard, the generator and transformer switches (2,300 volts), the 66,000 volt series transformers and the operator's office. From the generators the main 2,300 volt leads are brought up in fiber conduit to the gallery solenoid operated generator oil switches, closing to the 2,300 volt bus, which (except for disconnecting switches dividing it into three parts, each carrying two machines) runs through all the other generator switches. One of the generators is arranged with duplicate oil switches for throwing onto either of two of the three bus sections. As the transformer switches close onto two of these sections the arrangement makes it possible to operate any number of generators, up to the transformer rating, on either group of transformers. The 2,300 volt buses are made of ½ in. by 3 in. copper section, protected by barriers of ⅜ in. asbestos board.

Transformers.—The main groups of six 1,110 kw. oil-insulated, water-cooled transformers stepping up from 2,300 volts delta-connected to 66,000 volts with secondaries in star, and neutral grounded, are enclosed in separate concrete compartments on the first floor. Each recess is closed by a rolled steel door. The valve for the cooling water and the discharge from the coils are brought outside of the compartment at each side of the entry door, thereby avoiding the necessity of entering the compartment. Combined with the transformers is an oil-treating and filtering system, capable of purifying and drying 2.5 gal. each minute. This outfit comprises a motor-driven centrifugal pump, a sand filter and a lime drier, through which the oil is forced, and a pair of oil-receiving tanks, one for "good" oil and one for "poor" oil, each holding the contents of one transformer tank. With the arrangement of piping provided for connecting the transformer tanks with this oil-treating outfit, the contents of any transformer can be delivered to either receiving tank, treated, stored, or returned to the same or any other transformer in the station.

High Voltage Buses.—A novel feature of all the high voltage buses in this station is the use of Swedish-iron conductor, 0.375 in. in diameter, to increase the inductance of the station buses as a preventive of the entrance of lightning. Where the lines enter the station from the outside the copper

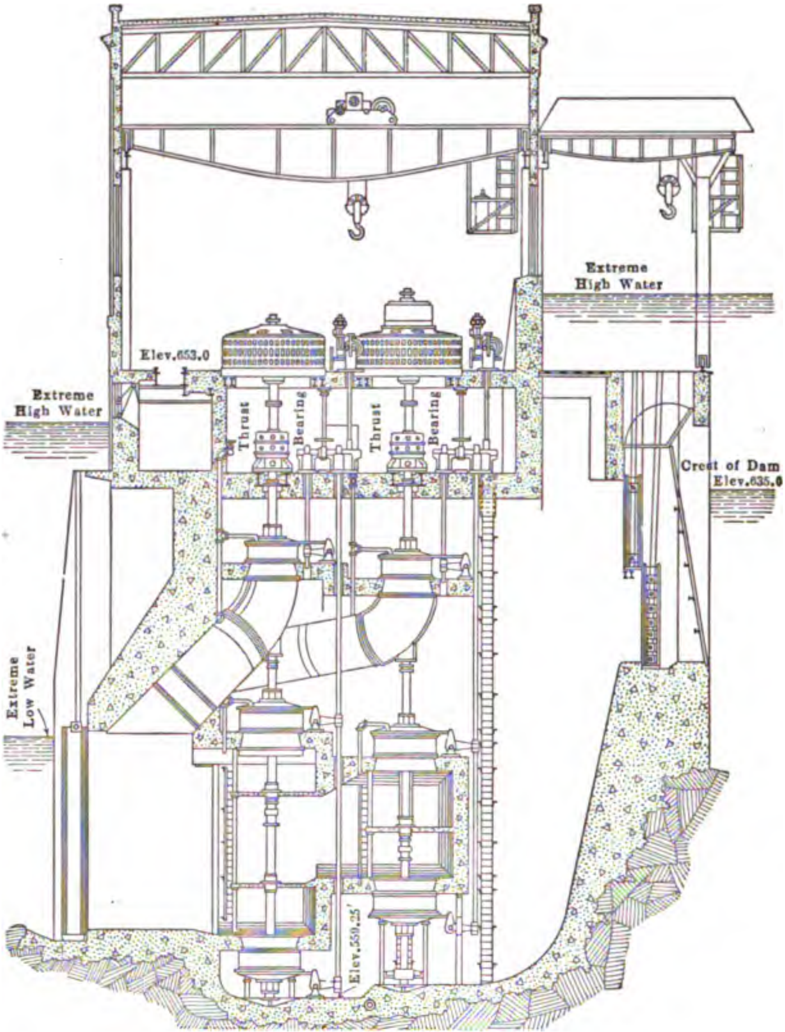


Fig. 26.—Hales Bar Development of the Chattanooga and Tennessee River Power Company 33 Miles Below Chattanooga, Tenn.

Work on this development was started in October, 1905, and the station formally placed in operation in November, 1913. It represents an expenditure, largely on account of construction difficulties in securing foundations for dam and power house, of approximately $9,000,000. The work is a monument of engineering genius and financial confidence in water powers on the part of Anthony N. Brady, the late president of the New York Edison Company, who made the completion of the project possible financially. The original and estimated cost of this development was $3,500,000 of which $1,500,000 was for dam, power house and lock and $2,000,000 for the construction of transmission lines. The initial installation of equipment consisted of ten sets of three S. Morgan Smith turbines mounted on a vertical shaft, each set driving a 3,133 kva. three-phase generator. The turbines are designed to operate under a low water head of 39.5 ft. and a high water head of 19 ft. The layout provided for 14 units and an ultimate station rating of 43,862 kva., which was completed in 1915 and 1916. The latter installation consists of four 4415 hp. turbines of single runner design connected to 3750 kw. generators, which operate at 100 r. p. m. The electrical equipment was furnished by the General Electric Company. T. E. Murray was consulting engineer, and John Bogart was in charge of the hydraulic and mechanical work.—*Electrical World*, November 15, 1913.

conductors are led directly to the lightning arresters, while the main lines to the 66,000 volt transformers are of iron tapped on the outside of the station wall and connected to the iron buses within.

III. A 58,000 Hp. Development Near Chattanooga, Tennessee

The power station shown in Figs. 26 and 27 with its transformer house is built of reinforced concrete. It is 66 ft. wide by 350 ft. long, comprising an operating building one story high and 220 ft. long and a switch and transformer house three stories high and 133 ft. long. The operating building consists of seven bays, each containing two turbine units, each unit

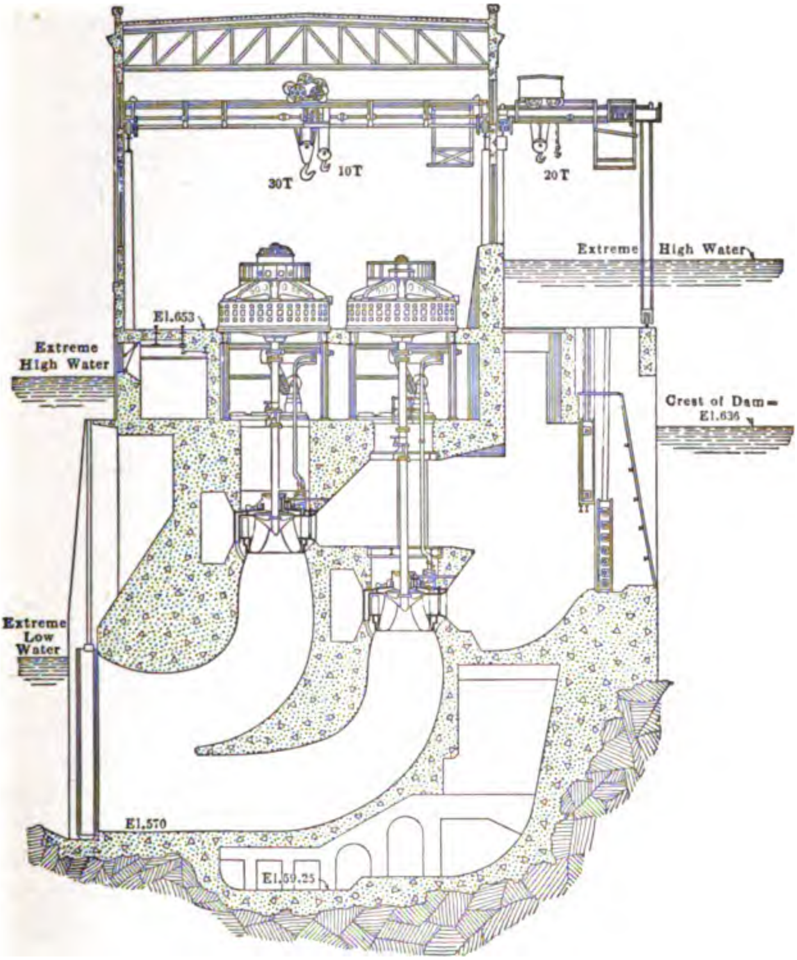


Fig. 27.—Arrangement of Single Runner Turbines for New Generators Installed in Hales Bar (Tenn.) Station in 1916

consisting of three turbines mounted on a vertical shaft with a 3,133 kva. 3-phase, 60 cycle, 6,600 volt generator on its upper end. Under ordinary stages of the river only two of the turbines are used for each unit. The two lower turbine wheels are 72 in. in diameter, and the upper wheel is 65 in. in diameter. The turbines run at 112.5 r. p. m., and each unit is capable of delivering 5,250 hp. under a head of 35 ft.

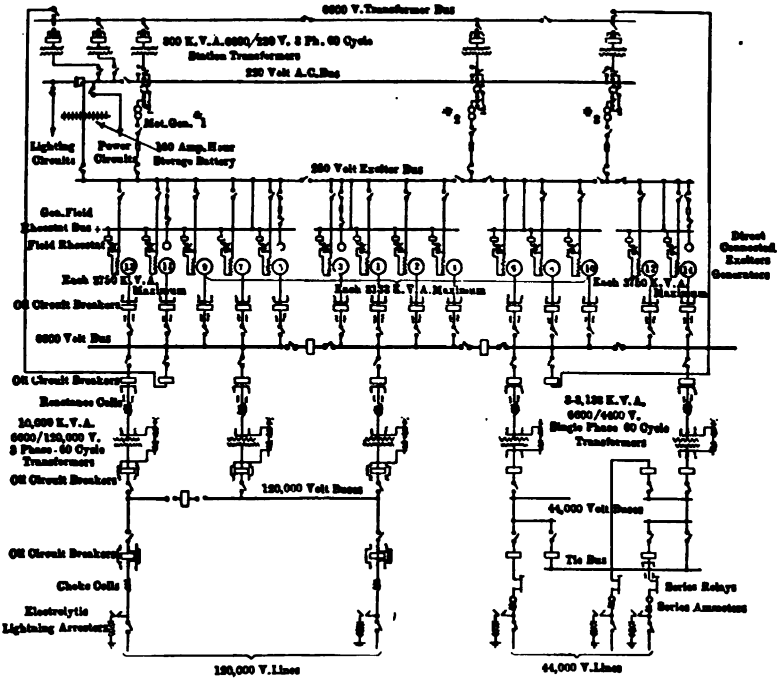


Fig. 28.—Layout of Equipment in Hales Bar Station Showing Present (1916) Arrangement of 44,000 Volt and 120,000 Volt Circuits

Hydraulic Features.—The hydraulic portion of this development was the most difficult of solution as the variation of flow is extremely large, ranging from 5,000 cu. ft. per second as a minimum to 320,000 cu. ft. per second during floods. For two months of the year the flow varies between 8,000 and 16,000 cu. ft. per second; for about four months between 12,000 and 60,000 cu. ft. per second; for about four months between 16,000 and 60,000 cu. ft. per second, and for about two months between 20,000 and 100,000 cu. ft. per second. During the shorter periods the maximum flow exceeds these figures. In view of these conditions it was found necessary, in order to secure uniformity of speed and regular output, to place three turbines on each shaft, the two lower ones operating during periods of high head and low flow, while the third turbine can be brought into play when there is more water but less available head. For low water the maximum head is 39.5 ft., while under flood conditions the backing up of water in the tailrace reduces the head to 19 ft.

Construction Difficulties.—During construction work on the dam and power house (1905–1913), when coffer-dams were constructed on the water side, it was found that great quantities of water spurted from fissures in the bedrock. Before concrete could be laid, these fissures had to be closed. This was accomplished by drilling 6 in. holes to a depth varying from 30 to 50 ft. Pipes were then sealed into the upper ends of the holes and cement forced under pressure into them to grout the fissures and seal them. This process was a slow and difficult one and had to be carried out for the foundations of power house and dam alike. At times 20,000,000 gallons of water were discharged from the fissures a day. In closing these subterranean waterways, something more than 200,000 sacks of cement were used. This work delayed the completion of the development to more than twice the calculated period.

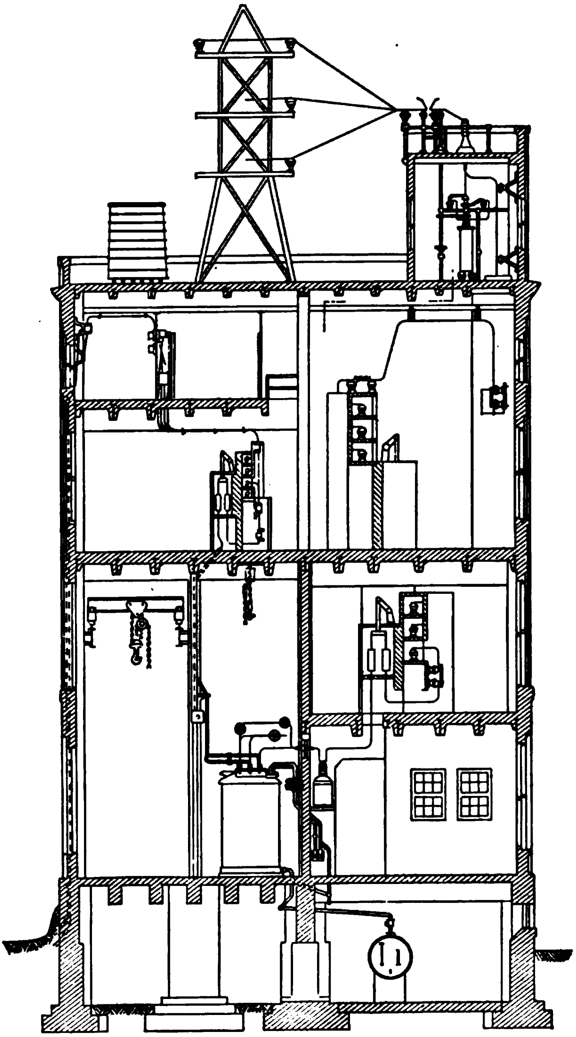


Fig. 29.—Substation and 44,000 Volt Switch-house of Chattanooga and Tennessee River Power Company

Changes in 1916.—The alterations to this station in 1916 included the addition of the four generating units provided for in the original layout.

New turbine wheels were selected for these units. Instead of three turbines on each driving shaft, as in the original installation, a single runner, inward and downward flow reaction turbine of the Francis type was utilized. This turbine is 82 in. in diameter and constructed after a design especially suited

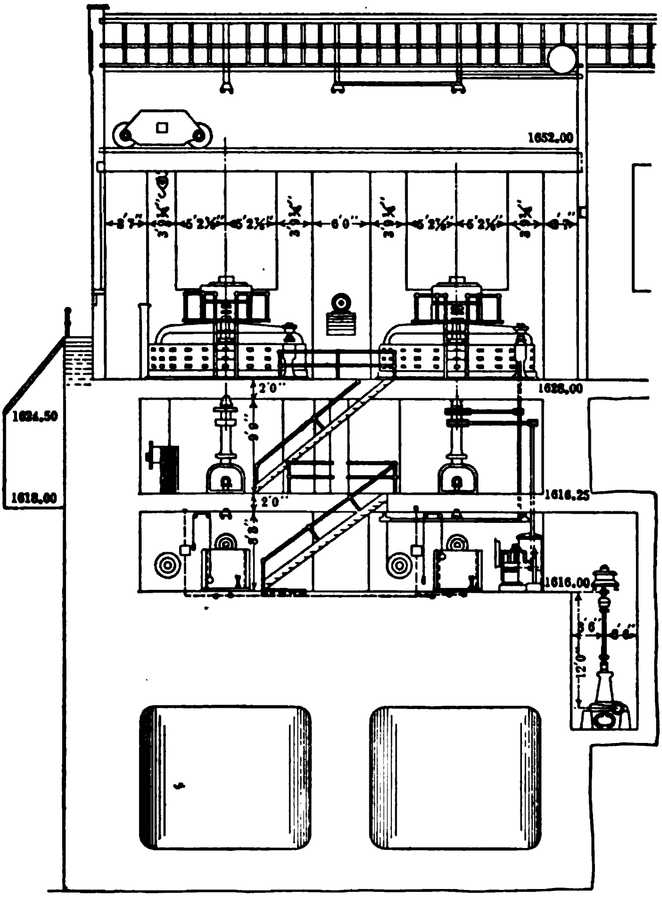


Fig. 30.—Marshall Plant of North Carolina Power Company near Asheville, N. C.

This plant is one of three operated by this company having a combined rating of 7,250 hp. It was placed in operation in 1912 and represented an expenditure when completed of $500,000. Of this amount $75,000 was spent in raising and rebuilding two and one-half miles of track of the Southern Railway. The turbine equipment was furnished by the I. P. Morris Company, Philadelphia, Pa., and the electrical equipment by the Westinghouse Electric and Manufacturing Company. The plant was designed by Charles E. Waddell, Asheville, N. C.—*Electrical World*, February 17, 1912.

to the plant conditions. Under test it has shown an efficiency better than 90 per cent. The arrangement is shown in Fig. 27. The new turbines develop 4,415 hp. 100 r. p. m. under a 38 ft. head. The new generators are 72 pole machines having a rating of 3,750 kw. at 100 r. p. m. 60 cycles, three-phase 6,600 volt. The ten old generators had a rating of 3,133 kw.,
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and were 64 pole, 60 cycle, three-phase 6,600 volt units operated at 112.5 r. p. m. The rating of the station as now equipped is 46,330 kw. at 120,000 volts.

IV. A 5,000 HP. DEVELOPMENT ON THE FRENCH BROAD RIVER NEAR ASHEVILLE, N. C.

The power house shown in Fig. 30 for a small southern development covers a ground area of 40 ft. by 76 ft., and is fireproof throughout. It is built of concrete to the floor line and brick from that point up. The windows are of steel and prismatic glass. From the floor to the eaves the height is 31 ft.; from the bottom of the foundation to the comb of the roof the height is 100 ft. A 50 ton electrically operated traveling crane extends the entire length of the building.

The down-stream side of the dam is curved in such a manner as to insure that the water will always cling to the surface and prevent the formation of a vacuum under the falling sheet, since it is generally conceded by engineers that the formation of a vacuum on the down-stream side is responsible for the trembling often felt in the vicinity of an over-fall dam. In the dam next to the power house are two circular mud gates, 7 ft. in diameter, which are opened and closed by an electrically driven pump in the generating station. The gates and cylinders are entirely submerged. The four penstock gates are among the largest cast-iron gates made. Each gate covers a clear opening of 18 ft. by 7.25 ft. and weighs 13 tons. They are operated in pairs by an electric motor.

The generating equipment consists of two 1,875 kw. three-phase alternators designed for 6,600 volts, 60 cycles, directly connected to two turbines. The units have vertical shafts with the exciters located on top of the alternators. The voltage is stepped up to 66,000 volts for transmission. The entire control of the plant is from the switchboard, all gates, switches, motors and valves being electrically operated.

V. STATION NO. 2 OF APPALACHIAN POWER COMPANY NEAR BLUEFIELD, WEST VA., ON NEW RIVER

The hydroelectric station shown in Fig. 31 utilizes a hydraulic head of nearly 50 ft. and contains four 6,000 hp. water wheel sets. Its solid concrete dam backs up the water to the tailrace level of another development above it. Above and at the side of the generating station an auxiliary spillway was built by cutting through a ridge to a natural sluice or gully paralleling the main stream. Additional spillway length of nearly 200 ft. is secured in this way, providing for six clear 31 ft. spans of flashboards.

The generating station measures 170 ft. by 50 ft., not including the concrete foundations and bulkheads containing the head-gates and trash-racks. The superstructure of the building is of steel and brick. It contains four

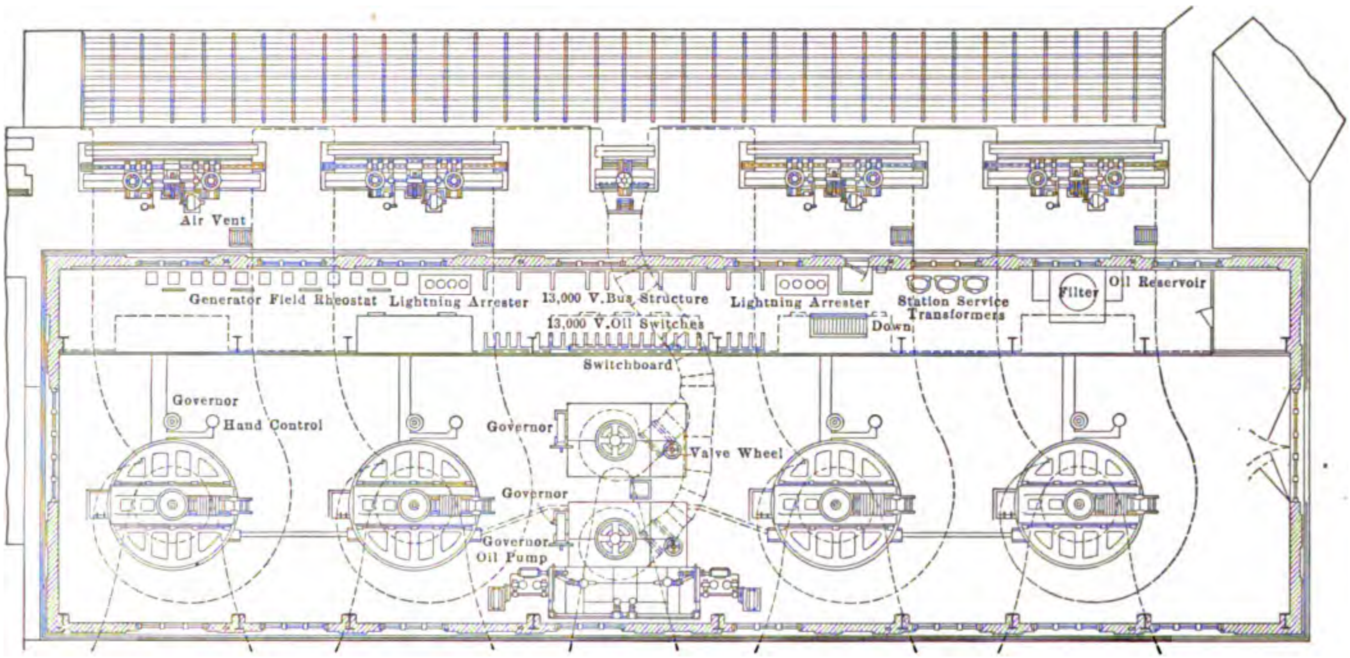
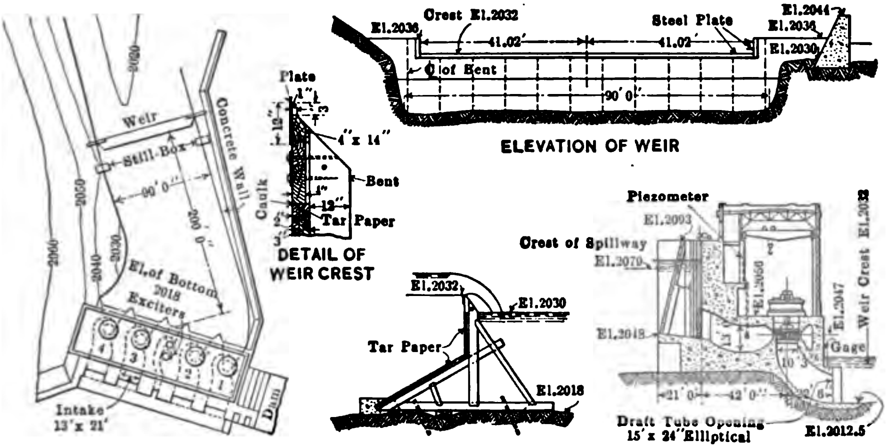


Fig. 31.—Plan of Station No. 2 of Appalachian Power Company on New River near Bluefield, West Va.

This is one of two stations having a combined rating of 34,500 hp. The first of five sites on the New River that was developed. The total possibility is 75,000 hp. in a range of 225 ft. drop in head. Station No. 2 contains four 4000 kw. water wheel units operating under a head of 50 ft. at 116 r. p. m. The station was built in 1912. The second station, No. 4, provides for three 3500 hp. vertical shaft single runner I. P. Morris water wheels which operate under a head of 38 ft. These units drive 13,200 volt, 60 cycle, three-phase General Electric generators at 97 r. p. m. H. M. Byllesby & Company, the operators, had charge of the engineering and construction of these stations with Viele, Blackwell and Buck consulting engineers. The transmission voltage to a common transformer house is 13,200 volts, the line voltage 88,000.—*Electrical World*, March 29, 1913, and *Southern Electrician*, November, 1912.

6,000 hp. single-runner Francis type water wheels, each driving a 13,200 volt, 60 cycle, three-phase 4000 kw. generator at 116 r. p. m. There are also two vertical shaft, 430 hp. water wheel-driven exciters running at 400 r. p. m. The rotating part of each unit is carried on a roller thrust bearing on top of the generator. Each of the main turbines requires about 1,200 cu. ft. of water per second at full load. The tailrace is 12 ft. deep, 90 ft. wide and about 350 ft. long, excavated in solid rock.

The electrical control equipment of this plant is restricted to that associated with the generators only and the 13,200 volt buses. All the high voltage and transforming apparatus is installed in a step-up station located about midway of the 13,200 volt lines, connecting it with several other generating stations.



PLAN SECTION OF WEIR CROSS SECTION OF POWER HOUSE

Fig. 32.—Details of Weir and Arrangements to Test 6000 Hp. Turbines in No. 2 Station of Appalachian Power Company on New River

Water Wheel Tests.—This development is of special interest because of the excellent efficiency of its turbines. The maximum efficiency under test of 93.7 per cent. is the highest of any turbine yet built. The specific speed (ft. lb. units, see page 27) at normal rating was 300. Such a high efficiency would be remarkable for a turbine of any type, but it is more so considering the high specific speed. The design of the draft tube is particularly important, and its cross-section was kept circular or elliptical at the outlet. Considerable care was taken in laying the concrete to keep the walls of the intake chamber and the draft tube as smooth as possible. The single draft tube saves the excessive losses usually found in double-runner units with the draft tubes discharging toward each other. Moreover, there is no sudden enlargement of the draft tube at the discharge of the runner such as is frequently found and causes serious losses. According to Camerer's formulæ for obtaining the increased efficiency of a large runner over a small one of the same type, the efficiency of the main turbine should be about 1.5 per cent. more than that for a model runner. However, this does not take into account the smaller proportionate mechanical losses in the large unit in place (the efficiency of the large wheel in place is from 3 per cent. to 4 per cent. higher than that given by a model runner) as compared with the mechanical losses in a model runner at the works of manufacturer, amounting to about 0.75 per cent., nor does it consider the better draft tube conditions in place.

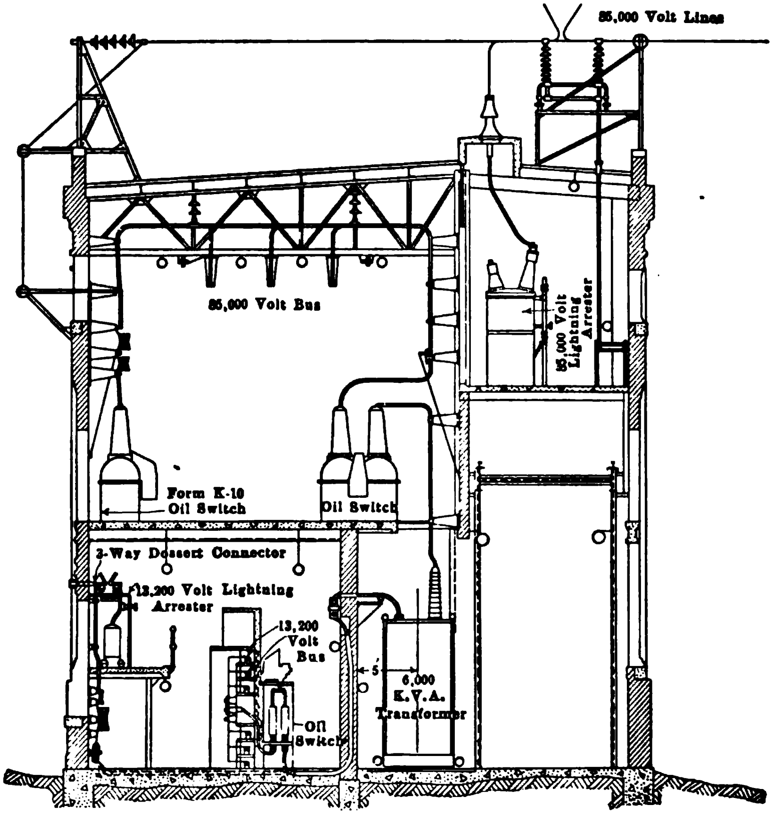


Fig. 33.—Joint Transformer House for No. 2 and No. 4 Stations of Appalachian Power Company on New River

During the tests the flow over a special weir was calculated by Bazin's formula, as this was considered to suit the conditions better and because Bazin's experiments have been conducted with so much greater care than experiments on which other weir formulae are based. It also gave more observation results. As compared with the Cornell experiments, Bazin's formula gives a discharge about 0.5 per cent. greater, and as compared with the Frese formula from 1 per cent. greater for the higher heads observed down to about 0.75 per cent. for the lower heads observed.

The over-all efficiency of the generating station to the switchboard after allowing for the losses in the generators, exciters, racks and headgates, etc., was 88 per cent. maximum eff., and from full load down to about 0.6 load the efficiency of the station was over 80 per cent.

VI. Station No. 2 of Calgary Power Company in Canada

The generating station building shown in Fig. 34 is 90 ft. long by 60 ft. wide, with foundation walls built up for 15 ft. of solid concrete. Above this they are tile plastered internally and externally. The generators, station-service transformers, storage battery and machine shop are on the main floor. From the lower floor access is had to the turbines. An upper gallery supports the lightning arresters and busbars. The hydraulic equipment of the initial installation comprised two 5,800 hp. vertical-type, single-runner, reaction turbines controlled by oil governors. These turbines are directly connected to two vertical-type generators, rated at 4,250 kva., 12,000 volts, three-phase, 60 cycles, 164 r. p. m. Excitation energy is obtained from one vertical turbo-exciter, rated at 75 kw., 220 volts, 600 r. p. m., and one motor-generator exciter of the same rating. A 50-ton electric crane is installed for handling all machinery. Direct current for remote control is furnished by an 80 amp. hr. storage battery, discharging at about 120 volts.

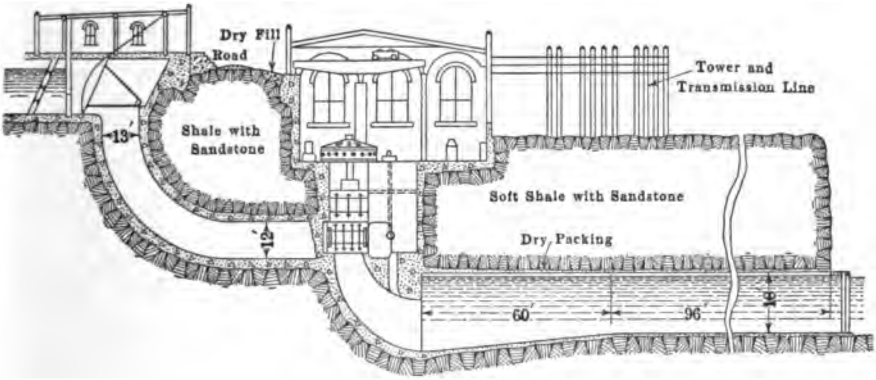


Fig. 34.—Head Works and Tailrace Tunnel of Station No. 2 Calgary Power Company in Canada

This is one of two plants on the Bow River. The site is at Kananaskis Falls, the other plant being at Horseshoe Falls two miles below. The station provides for two 5800 hp. vertical single runner reaction turbines, operating under a head of 70 ft., and direct connected to vertical generators rated at 4250 kva., 12,000 volts three-phase 60 cycles operated at 164 r. p. m. The turbines were furnished by the Canadian Allis Chalmers Company and the generators by the Swedish General Electric Company. The switching apparatus was sold by the Canadian Westinghouse Company. The plant was placed in operation in 1914. H. A. Moore was chief engineer and C. W. Allen construction superintendent.—*Electrical World*, April 11, 1914.

The generating station and headworks are on the south bank of a river about 1,000 ft. below the dam, and the water passes from the forebay to the head gates through a canal. From the draft tubes to the lower river the water flows through tunnels. The canal walls are lined with stone and concrete, except at its mouth, where the canal passes through solid rock. It is 700 ft. long by 80 ft. wide at the top and 50 ft. at the bottom, and permits an available depth of 15 ft. Water from the canal drops into two large pressure tubes (penstocks) built of concrete, 60 ft. in length and 35 ft. by 13 ft. in cross-section at the head gates and 12 ft. by 12 ft. at the scroll chambers. These connect directly into the two existing turbines through wicket gates, whence the water discharges under vacuum into draft tubes of concrete, 30 ft. in length, with a varying cross-section area of 81 sq. ft. at the entrance to 13 ft. by 16 ft. where it discharges into two tunnels inlaid with concrete and is carried down to the river again below the falls. With this arrangement a total head of 70 ft. is maintained, about 25 ft. being gained through vacuum in the draft tubes.

Two 3,000 kva., three-phase transformers step up the voltage from 12,000 volts to 55,000 volts, at which pressure energy is transmitted over aluminum conductors.

VII. Estacada Plant of Portland (Ore.) Railway Light and Power Company on Clackamas River

The generating station building shown in Fig. 35 is constructed of reinforced concrete. The roof is of reinforced concrete covered with paper and tar and gravel and supported by a steel truss. The dimensions of the building are 175 ft. by 60 ft.

Penstocks.—The five penstocks are made of steel plates 11 ft. in diameter varying in thickness from 3/8 in. at the intake to 1/2 in. at the discharge. They run in alternate bays of the dam structure and are supported at different points in their length by reinforced concrete beams. The penstock openings in the up-stream face of the dam are of rectangular cross-section, 11.5 ft. in diameter, with rounded corners. This rectangular section is not over 6 ft. long, the main part of the penstock being circular in form.

The supply gates are arranged for either hand or motor control. By means of the motor control the gates can be raised and lowered from the switchboard gallery. Each gate consists of six horizontal 15 in. 80 lb. I-beams secured to two 15 in. channels, one at either end, by means of angles, making a square gate 12.5 ft. on the side. The inner face of the head gate is covered by a 1/2 in. steel plate riveted to the I-beam structure. The raising and lowering of the gates is accomplished by means of two 15 in. 60 lb. I-beams, approximately 50 ft. long, secured to the I-beam structure of the gate by means of fishplates. These two stems are spaced 5.5 ft. center to center. On these two stems are attached two cast-steel racks, meshing with the mechanism. The teeth on the racks and pinions are staggered and shrouded.

Turbines.—Although provision was made in the building for five units, only three were at first installed, each of 6,000 hp. rating, consisting of two Victor-Francis bronze runners, 51 in. in diameter on one shaft—one left-hand and the other right-hand. The runners are flanged to bolt on to the forged shaft, and the flanges are so designed as to allow the dismantling of both runners through the rear end of the turbine unit. The runners are perfectly balanced. Each wheel casing is made up of four parts and is of scroll type, having a diameter at the inlet of 6.5 ft. At the point of inlet to the runners the casings are stiffened by ribs cast in one piece with the casing. These ribs are so placed as to facilitate the entrance of the water and increase its velocity in its passage from the casing to the runners.

The gates on each prime mover are cast of one piece of steel, the pivoting stems being so placed that the hydraulic pressure on the gates will tend to close them. The wheels discharge in the center of the unit into a common draft tube 8 ft. in diameter. The wheels are provided with two self-aligning, self-oiling, generator-type bearings heavily babbitted and grooved for oil. Water-cooling coils have been placed in the oil space. The swivel-gates on each runner are operated by arms and links attached to cast-iron gate rings. The strength of these links and arms is less than that of the gate itself, to ensure an external rather than an internal breaking to the turbine casing in case of accident. Oil-pressure governors are used of a normal rating of 30,000 ft. lb. The oil pump is belt driven from the unit on which it is installed. The governor is equipped with a 125 volt direct current motor with switchboard control. These governors are "dead-beat" in action and are so adjusted as to open completely or close the gates in two seconds. In addition to this governor each unit is provided with an emergency closing device, which is mounted on the back bearing.

A test of the water wheels at 81 ft. head showed an efficiency of 80 per cent. at full load, and 82.5 per cent. at three-fourths load. The input to the wheels was determined from the actual vertical head of water and Pitot tube measurements. The computed efficiency for 240 r. p. m. and 81 ft. head from the maker's tests for three-fourths load gave 84 per cent. The runaway speed of the wheels is 410 r. p. m., and they are designed to withstand this speed, although the regular running speed is only 240 r. p. m. The draft tubes are circular in section at the connection to the bedplate and elliptical in section at the point of discharge into the tailrace. They are made of $\frac{5}{16}$ in. steel plate, rolled with all points securely riveted, beveled and calked and made air-tight.

Generators.—The generators are located on the main floor of the power-station and are directly connected to the water wheels. They are each of the revolving-field type rated at 3,667 kva., 11,000 volt, three-phase, 60

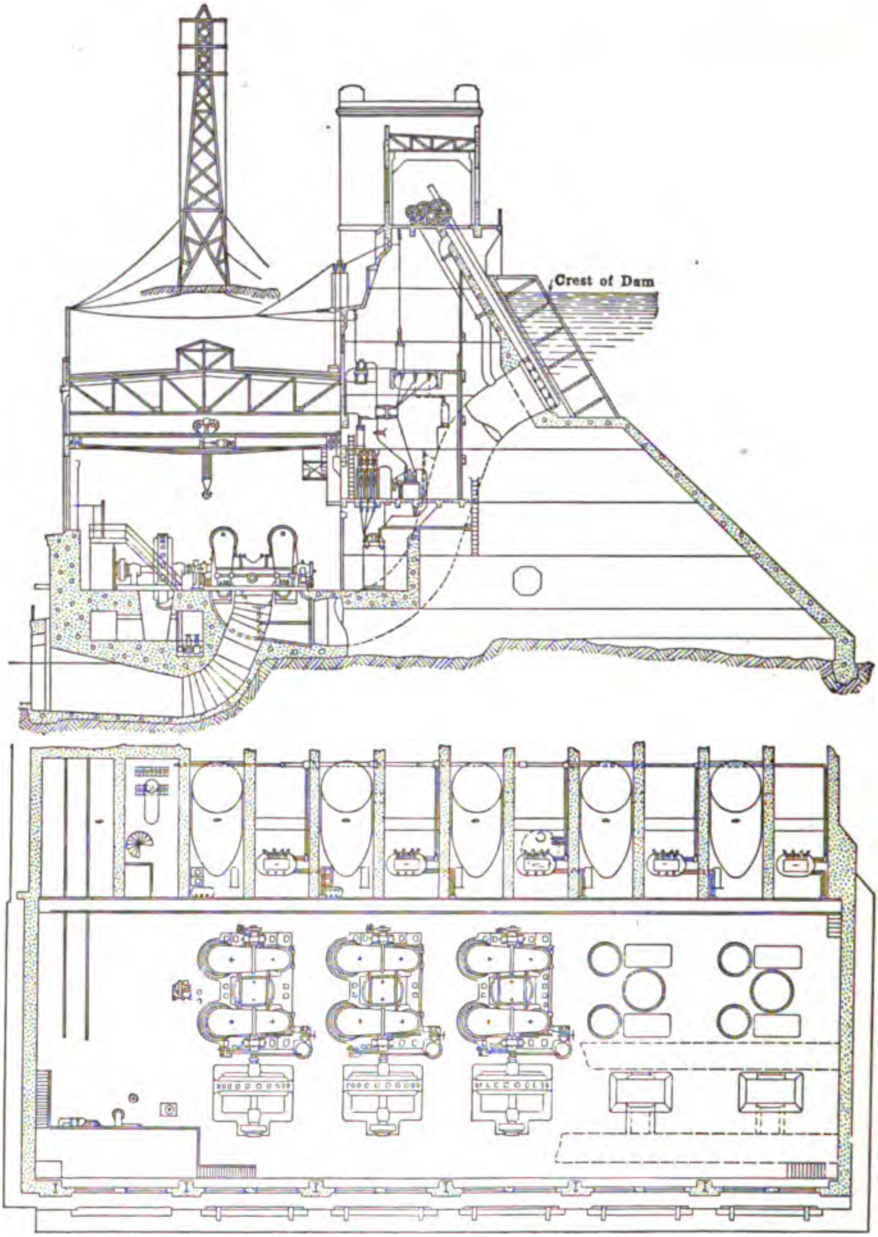


Fig. 35.—Bulkhead Section and Plan of Dam and Power House of Estacada Plant of Portland (Ore.) Railway Light and Power Company on Clackamas River

This station was built to operate in tandem with an older plant 3.5 miles up the river to take advantage of the storage during low water months. Plant was placed in operation during November, 1911. The layout calls for five 6000 hp. Victor-Francis turbines each connected to a 3667 kva., 11,000 volt, three-phase, 60 cycle generator operated at 240 r. p. m. The head on the turbines is 81 ft. The turbine runners are 51 in. in diameter on one shaft (one right hand and the other left hand). The initial installation was three units. The transmission voltage is 57,100 volts.—*Electrical World*, July 13, 1912.

cycles, with thirty poles, and operate at 240 r. p. m. The generators are mounted over deep openings in the floor which connect with two tunnels or passageways running longitudinally under the station floor. These tunnels contain hydraulic piping and electrical conduits and cables and afford an excellent natural ventilation for the generators. The compound wound exciters are overhung on the end of the generator shaft and have each a rating of 60 kw., 125 volts, 240 r. p. m. with six poles. In addition to the directly connected exciters there is also a motor-generator exciter set of 85 kw., 600 r. p. m., 125 volts compound wound, and a water wheel to which the set is directly connected.

An unusual feature is the use of a double-pole double-throw switch on the alternator switchboard panels for rendering the alternator switches automatic while being synchronized but non-automatic thereafter. The universal time-limit overload relays serve to indicate overloads or short circuits by lighting a special red lamp, thereby calling the operator's attention to the conditions when the operation of the alternator oil switch is rendered non-automatic by the above-mentioned switch. The step-up transformers are of the three-phase design, oil-insulated, water-cooled, 11,000/57,000 volts and rated at 3,750 kva.

Transformers.—Adjoining the main generating floor in the high-voltage addition to the generating station are the closed concrete cells for the main step-up transformers and the oil switch and generator-bus cells for the 2,300 volt circuits.

The controlling switchboard is mounted on a gallery between the two inner main penstocks and overlooking both the exciter bay and the generator floor with communicating galleries connecting with the second story of the high-tension structure, on which are installed the high-tension line and tie-switches.

From the 2,300 volt buses oil switches and double throw disconnecting switches connect to the primaries of the 2,300/33,000 volt, oil-insulated, water-cooled, step-up transformers, of which two groups of three 1,666 kva. units are installed. These are enclosed in separate concrete compartments with steel doors, and with the cooling water connections accessible from the passageway outside. The secondary lines from these transformers are led up through the ceiling to the high-voltage line switches, designed, like the transformers, etc., for 60,000 volts operation, the pressure at which the transmission line will eventually operate.

In the basement of the generating station beneath the transformer cells an oil-treating system capable of purifying 850 gal. of oil an hour is installed. A hydraulic ejector operating on the 50 ft. head available between the headrace and the tail-water has also been utilized for the purpose of producing a vacuum line used for cleaning machines in the generating station. The generating room is served by a hand-moved crane and electric hoist; while running opposite the transformer bays and to the turntables connecting with a spur-track across the turbine-room floor is a 30 in. narrow-gauge track on which moves a flat hand-car having its deck at the level of the transformer cells so that any of these units can be transported about the station.

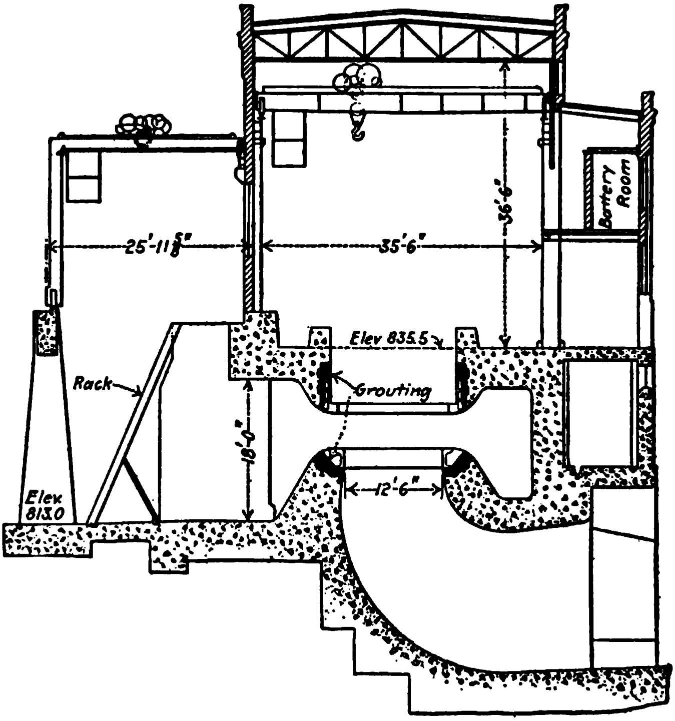


Fig. 36.—Coon Creek Station of Northern Mississippi River Power Company near Minneapolis, Minn.

This plant was built during the latter part of 1913 by H. M. Byllesby & Company. Its entire output is used by the Minneapolis General Electric Company and is tied in with other water power plants at Taylor's Falls and St. Anthony Falls. Five single runner Allis Chalmers vertical type water wheels, each rated at 2100 hp., operate under 17.5 ft. head and drive General Electric direct connected generators rated at 1625 kva. and 2300 volts at 62 r. p. m. The station is laid out for seven of these units. Only motor-driven exciters are used since all the interconnected stations are operated as one system. The H. M. Byllesby & Company acted as engineers and constructors for this plant.—*Electrical World*, November 29, 1913.

Duplicate exciter buses are provided in the station, only the positive side of the circuits being brought to the switchboard. Special throw-over switches are installed for transferring the generator-field circuits from one exciter bus to the other without interruption. The negative side of the exciter circuits is carried directly to the several machines, switches being mounted on the frames of each for access from the floor.

VIII. COON CREEK DEVELOPMENT NEAR MINNEAPOLIS, MINN.

The station is of brick with a structural-steel frame and concrete floor. The plant is designed to utilize a head of 17.5 ft. with seven units having a total rating of 14,700 hp. A spillway dam 1,000 ft. long has been built across the wider and shallower channel, and the plant structure has been built over the narrower and deeper channel. The entire work thus consists of earth embankments with core walls 557 ft. long, the generating station and retaining section, 498 ft. long, including sluice-gates, log chute and fishway, and the spillway, 1,000 ft. long, making the total length of the structure 2,055 ft.

The forms for the draft tubes were constructed in sections, which are removed from the concrete sets and used over again. Construction of the large draft tubes and scroll-case forms in such sections has the advantage of allowing the sheeting to be placed on the shore and accelerates erection, since both forms and excavation can be worked on at the same time. Each tube is designed to discharge 1,320 cu. ft. per second at 17.5 ft. head. The spillway has been designed for a maximum flow of 80,000 second ft., although 60,000 second ft. is the maximum stream flow of which there is any record.

Vertical type single-runner water wheels drive direct-connected generators rated at 1,625 kva. and 2,300 volts at 62 r. p. m. These machines deliver three-phase 60 cycle energy to the station buses. It is stepped up to 13,200 volts by delta-connected 1,375 kva. transformers. This combination of 2,300 volt generators and step-up transformers was found to be less costly than equivalent 13,200 volt alternators would have been under the conditions of low speed and large size imposed by the low head available.

IX. HYDROELECTRIC STATIONS OF NEW ENGLAND POWER COMPANY ON DEERFIELD RIVER

The generating station of Fig. 37 consists of a brick and steel building with concrete foundations erected at the lower end of a row of penstocks delivering water to the wheel casings, which are located outside of the generating station and connected by short shafts to the generators. The latter are mounted in an operating room which extends the entire length of the building.

This station, known as No. 2, is equipped with three 2,000 kva. units, consisting of a 2,300 volt, three-phase, 60 cycle, revolving field alternator driven through a horizontal shaft by a 3,000 hp. double-runner, central-discharge turbine operating at 257 r. p. m. The head is 60 ft.

The switchboard is installed on the operating floor opposite the water wheel entrances. At one end is a 2,300 volt bus structure, with low-voltage oil switches installed in concrete cells having asbestos intermediate

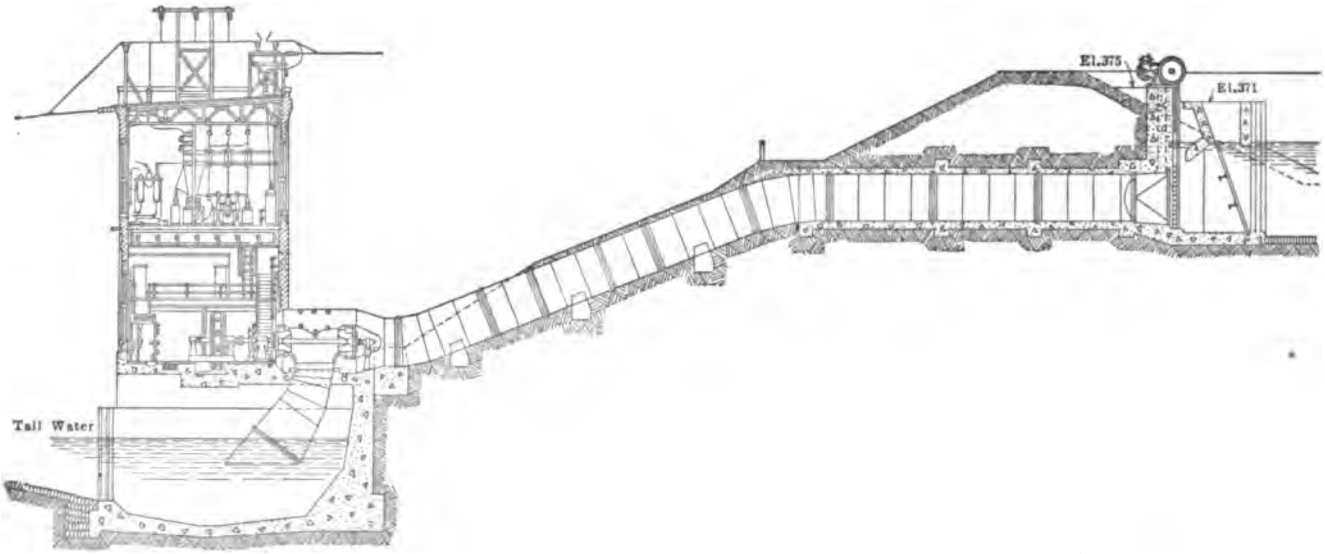


Fig. 37.—Plant No. 2 of New England Power Company on Deerfield River at Upper Bardwell Falls

This station contains three 2000 kva. 2300 volt, three-phase, General Electric generators each driven by a 3000 hp. horizontal shaft double runner central discharge Wellman-Seaver Morgan turbines at 257 r. p. m. The head on the turbines is 60 ft. Station No. 3 at Shelburne Falls operates under a head of 64 ft. and contains the same equipment as station No. 2. The latter station was built in 1911–12. The design and construction was done by the Power Construction, George W. Bunnell in charge with J.-G. White & Company and Chas. T. Main advisory engineers.—*Electrical World*, December 28, 1912.

barriers, the cables from the machines being run to the cells in conduit which is laid in the floor. A gallery is provided at the end of the operating room above the bus cells to carry a storage battery for operating switch and other minor equipment. In the upper story extending along the station over the operating room is a transformer and high-tension oil-switch room designed for 66,000 volts and equipped with a 50,000 lb. chain hoist for handling transformers between this room and the operating floor below. Upon the tar and gravel roof is mounted a steel and pipe frame structure supporting the insulators which carry the incoming and outgoing lines, with horn-gaps and lightning arrester connections.

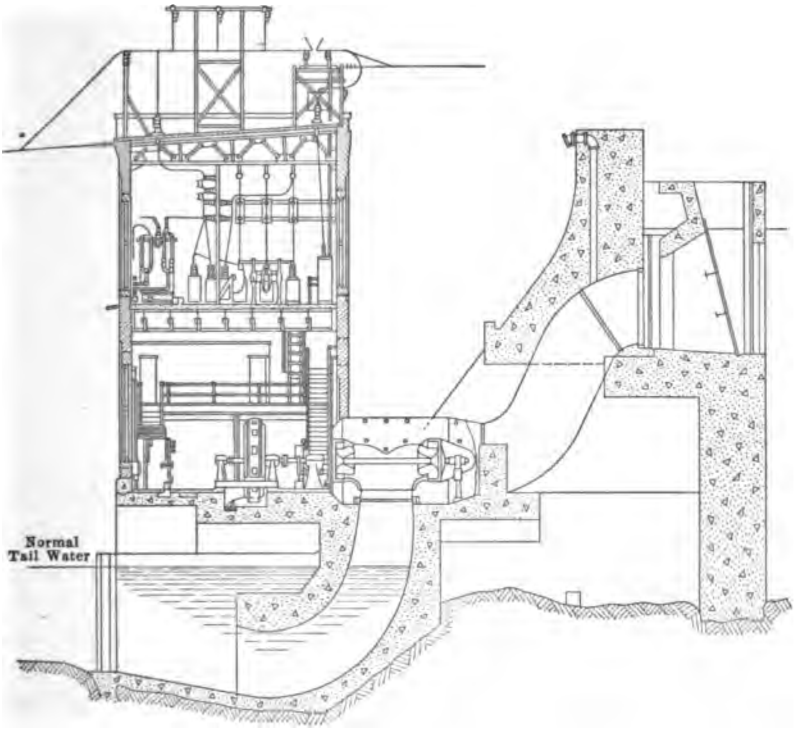


Fig. 38.—Plant No. 3 of New England Power Company on Deerfield River at Shelburne Falls

The penstocks are built of riveted steel varying in thickness from ¼ in. at the upper ends to $\frac{5}{16}$ in. at the bottom. The inside diameter is 10 ft. and they are about 160 ft. long and are anchored into the hillside by concrete piers 26 ft. apart.

Station No. 3.—The dam shown in Fig. 38 has a height of 60 ft. and is 50 ft. thick at the base and 5 ft. wide at the top, its length being about 375 ft. The spillway is of an ogee shape, and the power house is situated at one end of the dam on the down-stream side. Short penstocks connect intakes on the up-stream side of the dam with the wheels. The intakes are equipped with screens and gates to meet all requirements and anticipated operating conditions, while the dam is provided with sluice-gates which facilitate the discharge of water, ice and débris. The location of this station at the bottom of a gorge greatly facilitated handling materials during construction by gravity, and an extensive sand-washing and stone-crushing plant was a feature of the work.

The three 2,000 kva., 2,300 volt, 60 cycle generators, each driven by double-runner Francis-type turbines are installed along the middle of the operating room with about 22 ft. between shaft centers and deliver energy directly to the low-tension switches and buses. There are two 100 kw., 125 volt exciters, each direct-connected on a horizontal shaft to a 2,300 volt induction motor running at 900 r. p. m. The transformer equipment consists of two 3,000 kva. oil-insulated, water-cooled units wound with 2,300 volt primaries and 66,000 volt secondaries. These transformers are connected in delta on the low-tension sides, and in star on their high-tension sides. The neutrals on the high-tension sides are carried on insulators for a short distance away from the transformer tanks so that they may be disconnected and the system operated ungrounded if necessary. Around each transformer is built a wall of concrete 8 in. thick, with a short brick section which may easily be knocked out on the side nearest the hatchway leading to the operating room. This basin serves as a temporary receptacle for oil in case of leakage.

X. SWEDISH SUBTERRANEAN HYDROELECTRIC STATION RATED AT 20,000 HP.

The installation shown in Fig. 39, while not an American development, is very interesting because of the location of the station equipment.

This plant utilizes rapids which are about 2.8 miles long. A maximum discharge of 25,000 cu. ft. per second has been observed during periods of floods, but this is reduced during three months of the year to 1,900 cu. ft. and is known to have been as low as 850 cu. ft. per second. The part of the rapids developed has a head of 78 ft., but whenever it is considered advisable to increase this head a very material addition can be had by making use of the rapids which are found above the present dam. The dam is built on bedrock with steel and concrete piers faced with steel plates on the up-stream sides. The spillway crest of the dam has an elevation of 76.45 ft. There are 64 wooden gates running in removable steel guides, providing large openings for removal of débris, four steel head gates, and one large steel sluice-gate, which is 19.7 ft. wide and 26.3 ft. deep divided horizontally into two parts. Through the sluice-gate provision is made for discharge during floods and for draining the pool for repairs of the dam and the screens. The reason for dividing this gate into halves was to avoid a large superstructure and to make available the use of the lower part of the gate for regulating the water level, this part always being free from ice, even at very low temperatures. All the gates may be operated either by hand or by electric motors.

Turbines.—The wheel chambers, blasted into the rock, have a steel lining, back-filled with concrete, and are of a cylindrical shape, 21.3 ft. in diameter. Four double-runner Francis turbines, each rated at 5,100 hp. at 225 r. p. m., are mounted in a horizontal position at the bottom of these chambers, with the shaft centers 24 ft. above the lowest tailrace level. Two wheels discharge into the same tailrace tunnel. These tunnels are about 5,000 ft. long and have a 322.8 sq. ft. cross-sectional area. At a distance of 164 ft. from the turbines there are large pockets in the roof, each of about 2,000 cu. yds. These pockets are interconnected and provided with vertical shafts, the object being to prevent water hammer. So far tests and experience have shown that this arrangement is quite satisfactory in its working.

The wall between the generating room and the wheel chamber has a minimum thickness of 18 ft. and consists mainly of the natural rock foundation. The generator room is 31 ft. wide and 105 ft. long. It has an arched reinforced concrete roof. The maximum height of the room is 29.5 ft. Between the subterranean generating room and the transformer house an inclined tunnel serves as a communication. In the bottom of this tunnel there are ducts for cables and fresh air. The tunnels and the shafts are lined with reinforced concrete. From the wheel chambers steel tubes, 4.26 ft. in diameter and back-filled with concrete, lead through the rock into the generating room. Through these tubes, the diameters of which have been made as small as possible in order to preserve the rock, are taken the turbine and rocker-ring shafts, spaced 2.5 ft. center to center. This single rocker-ring shaft is in the wheel chamber divided into two shafts placed diametrically opposite each other along the turbine. The governors are provided with hydraulically and mechanically operated hand-controlled, gate-setting devices. Arrangements are made for controlling from the main switch-board the small electric motors that are provided for synchronizing the units.

Generators.—The generating equipment consists of four 4,500 kva., 6,600 volt, three-phase units operating at 225 r. p. m. and 60 cycles. They are totally enclosed and provided with intake and outlet for cooling air. The warm air, liberated from the top of the generators, rises through a vertical shaft to the pump and fan-house directly above, whence in the winter it is distributed for heating of switch house and also for heating the ice racks. For the intake air, a small tower on the switch house is provided. The air enters through double screens and is conducted through the main tunnel to channels in the generating-room floor, the latter terminating in the pits under the generators.

Switch House.—The switch house contains all the transformers and the switch gear. The step-up transformers are divided into two groups, each of three single-phase transformers placed in separate fireproof compartments. The transformers are delta-connected on the 6,600 volt side and star-connected on the 50,000 volt side. Each group can carry continually 8,650 kva., which corresponds to the load of two generators. A reserve transformer of the same size is also installed. All the transformers are oil-insulated and water-cooled. In order to protect the oil from expansion and moisture the oil tanks are provided with expansion chambers. Further protection against moisture in case the transformer should stand unloaded for any length of time has been provided by the installation of an electric-heating element operated on a low-voltage circuit. The temperature of the oil can be read on thermometers on the switchboard. The transformers are also provided with signal thermometers which sound an alarm in case the temperature of the oil or the cooling water should rise above a certain predetermined value.

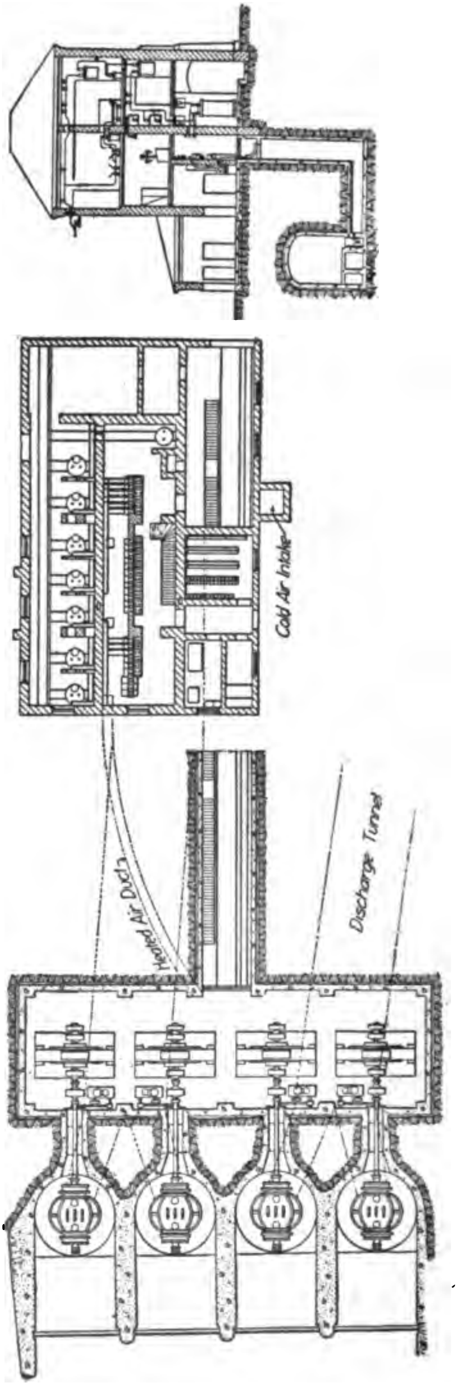


Fig. 39a.—Features of the Plant Layout Shown in Fig. 39b

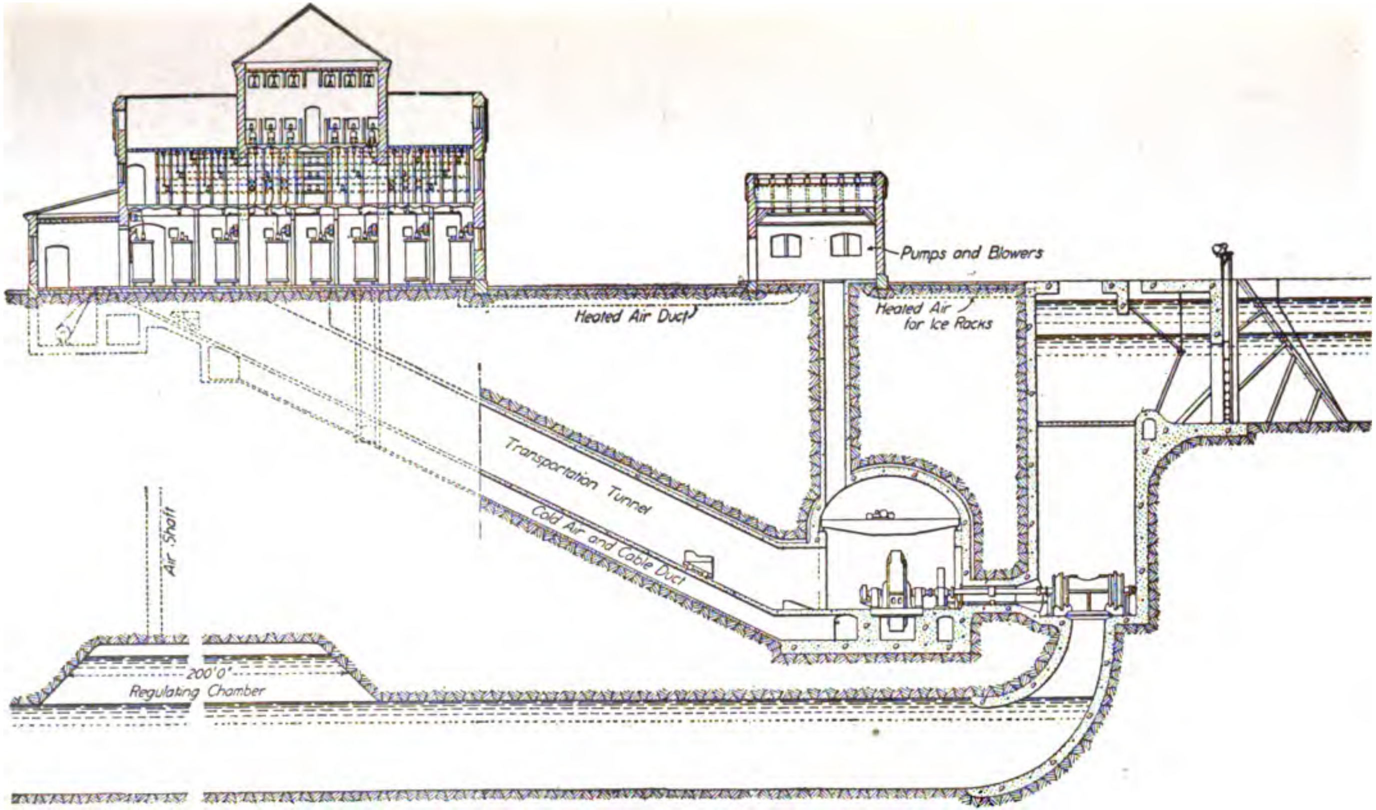


Fig. 39b.—Mockjard Plant of West Dal River Power Company on West Dal River in Sweden

This station has a rating of 18,000 kva. and is part of a 65,000 hp. interconnected system. It was built in 1908 at a cost including hydraulic, electrical and switching equipment of $49 per hp. The station provides for four 4500 kva., 6600 volt, three-phase, 60 cycle generators operating at 225 r. p. m. Each generator is driven by a double runner horizontal Francis turbine rated at 5100 hp. under 78 ft. head. The shaft center is 24 ft. above lowest tailrace level. Energy is transmitted over a 20 mile line of seven strand aluminum cable 120,000 c.m. on towers of wood poles spaced 540 ft. average. Transmission voltage is 50,000.—*Electrical World,* May 10, 1913.

In the generating station there is only one disconnecting switch at each generator terminal and one similar switch for the neutral, the latter being grounded through a common neutral resistance calculated for two and one-half times the normal rating of one generator under thirty seconds.

Cost of Development.—Another very interesting point about this development is its total cost per hp. developed, which is as follows:

Water rights and real estate		$223.640
Dwelling and Engineering		17,240
Dam, Flume and Tunnels		478,980
Generating Station and Switch house (buildings)		102,320
MACHINERY:		
Turbines and governors	$31,720	
Generators	64,250	
Transformers	28,290	
Switch-gear	42,360	
		166,620
Total cost		$988,800

Cost per hp., $49.00

XI. GATUM HYDROELECTRIC STATION FOR PANAMA CANAL

The Gatum station shown in Fig. 40 is 61 ft. wide by 137 ft. long and has an extreme height of 74 ft. The building is designed on the unit principle to admit of future extension, and consists of a single room open to the roof, exposing the trusses on which are laid the reinforced concrete roof slabs, which, in turn, support red tiles. The walls are of poured concrete and are 30 in. thick to the level of the crane rails near the cornice. The exterior overhang of the main roof is 13 ft. 2 in. and that of the monitor roof 4 ft. 8 in., the exceedingly large proportions being adopted as a shelter from the tropic rains as well as from the heat of the sun.

Pipe Lines.—The pipe lines are led down to the rear of the generating station on a uniform slope from the spillway and are connected to the turbines in the generating station through 90 deg. bends with radii of 70 ft. A pilot-tube testing apparatus can be attached to each of the pipe lines while the water wheels served are in operation. A pair of portable tubes for taking readings in planes of the pipe at 90 deg. from each other has been supplied for this purpose. The gross head available varies from a maximum of 91 ft. in the extreme flood times to a minimum of 79 ft., to which level the reservoir may possibly drop toward the close of the season. The plant is designed, therefore, to develop the full water output when operating under an effective head of 75 ft. For three or four months of the year there is absolutely no rainfall. During this period it is desirable to conserve the water as much as possible, and maximum efficiency was accordingly demanded for the equipment, both the water wheels and generators. Water is taken from the forebay through passages 12 ft. wide, fitted with wrought-iron racks 29 ft. 7 in. high, to prevent débris from entering the pipe lines.

The water is admitted into the pipe lines through three head gates, 10 ft. 6 in. in diameter. These gates are of massive cast-iron construction, the seats where watertightness is required being made of bronze. These gates are equipped with automatic control devices, consisting of a limit-switch geared to one of the gate stems and a float switch actuated by the water in the pipe. When the gate has opened a sufficient distance so that the pipe line can be filled in about five minutes, the limit switch opens the circuit and stops a 15 hp. 220 volt induction motor operating at a speed of 750 r. p. m. The gate remains in this position until the pipe line is filled and the water rises in the 36 in. diameter air-vent pipe just below the gate. A

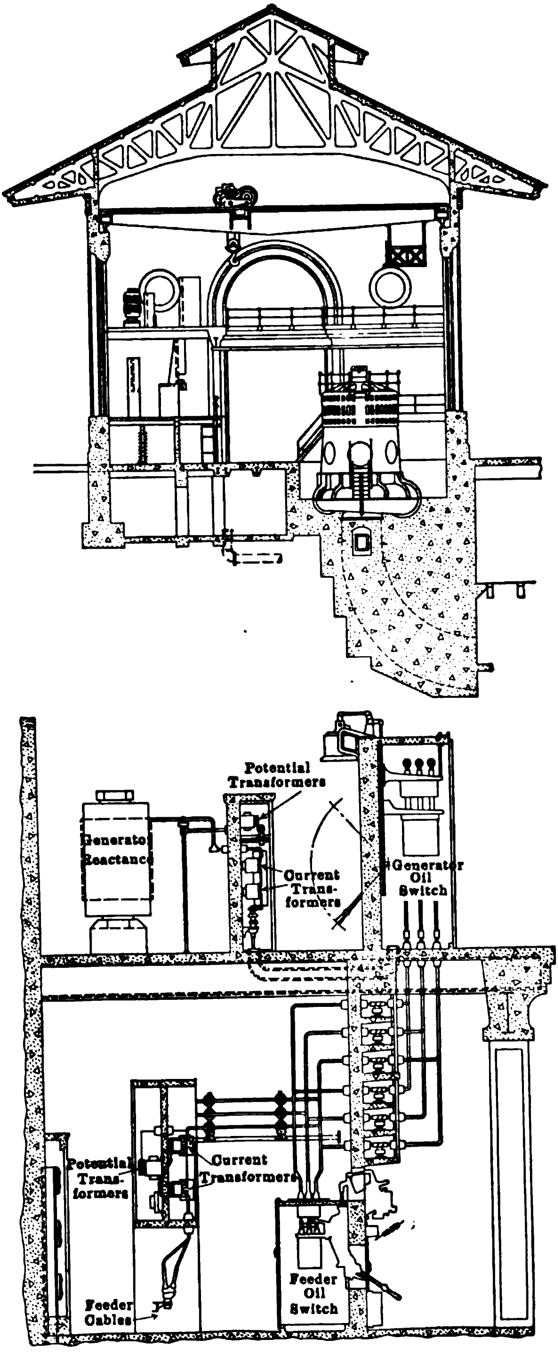


Fig. 40

Fig. 40.—Gatun Station, Panama Canal, Section Through Generator and Switching Elements

The station contains three 2000 kw. three-phase, 2200 volt, 25 cycle generators driven by 50 in. vertical single runner Francis turbines made by Pelton Water Wheel Company. The turbines operate under a head of 75 ft. at speed of 250 r. p. m. The center of the runners is 20 ft. above the tail water. Turbines are of the spiral case pattern.—*Electrical World*, July 4, 1914.

float switch is then actuated and the motor circuit is again closed. Each of the gates is bolted to a pipe line having a diameter of 10 ft. 6 in. and an average length of 420 ft. The pipe lines are made of 3/8 in. steel plates in courses of 8 ft. long, each course being made up of three sheets to form the circumference. The center of each course is fitted with a 3 in. by a 3/8 in. Z-bar ring, which is also made in three sections. After the pipe was riveted together at the plant, the outside was covered with a layer of reinforced concrete to prevent rust.

Power House.—The interior of the building has four principal floors, namely, a pit for the three 2,500 kva. complete units, a main floor and two galleries. The turbine pit, with an area of over 2,100 sq. ft., is 6 ft. below the level of the main floor and is reached by iron stairways descending alongside the turbines. The main floor is divided into two parts, one being partitioned off and devoted to the use of the electrical equipment and the other forming an uninterrupted passage on the longitudinal axis of the building, terminating with two large entrance doors at either end. Easy access to railway cars is afforded by means of a track which enters this floor from grade through the northwest door, thus giving easy facility for handling heavy machinery by the 30 ton electric crane running the length of the building overhead.

Generating Units.—Each of the three 2,500 kva. main generating units in the generating station is driven by a 50 in. vertical single-runner Francis turbine. Each turbine has a maximum rating of 3,600 hp. when operating under an effective head of 75 ft. and at a normal speed of 250 r. p. m. The turbines are at such a height that the center of the runners is 20 ft. above tailrace. The water is discharged from the steel-lined concrete draft-tubes, which are 71 in. in diameter at the point where the water leaves the runners, and increase in size until at the outlets they have an elliptical section of 9 ft. by 17 ft. The turbine is designed so that the runner exerts an upward thrust of 20,000 lbs. when working at its full rated output, thereby releasing the thrust bearing of that amount of load.

Small electric motors are connected to the governors and are used for varying the speed of the main units for synchronizing purposes. A device is also provided on each governor for varying the permanent drop in speed from no load to full load. This device can be adjusted for any variation from a 5 per cent. drop in speed to absolutely constant speed and from friction load to maximum load. These governors are also fitted with hand-control mechanism for adjusting the gates independently of the oil pressure. The oil pressure for actuating the governors is supplied by two pumping units, driven by 10 hp. induction motors at a speed of 375 r. p. m., each pump being capable of serving the governors on all three units. The governors work on an open system, no vacuum chambers being used.

The three main generating units are of the vertical revolving field type, each being provided with a directly connected exciter. The generators are designed for three-phase, 2,200 volts, 25 cycles with a continuous rating of 2,000 kw. at 0.8 power factor. The exciters are rated at 50 kw., with 125 volts and each is capable of furnishing exciting current for two generators under maximum load. The generators are carried on heavy cast-iron distance rings and the stationary armatures are bolted to these rings. The thrust-bearing and upper-guide-bearing support consists of a very rigid iron casting bolted to the top of the stationary armature.

Current limiting reactors are provided to give 5 per cent. reactive drop, with three-phase, 25 cycle current at 2,500 kva. and 2,200 volts. While the generator windings are sufficiently rigid to withstand the strain of a short circuit under full load, these reactors will reduce the shock on the windings and will also make the operation of synchronizing the machines easier and safer.

Exciters.—In addition to the directly connected exciters, two motor driven exciters are used. These consist of 100 kw., 125 volt, 500 r. p. m. generator directly connected to a 150 hp. 2,200 volt, 25 cycle induction motor. These exciters can also be used for charging the control battery. The main switchboard is of the benchboard type, with vertical rear board for relays, watt-hour meters, graphic instruments and the control battery equipment. The exciters are controlled from the benchboard, but the electrically operated exciter switches and field switches are mounted on a separate board placed so as to make the exciter connections as short as possible. This arrangement eliminates the exciter buses and the main connections from the control board. On account of the great distance covered, energy is transmitted at a pressure of 44,000 volts. The step-up transformers are, however, not in the generating station, but in a substation at some distance therefrom. The plant generates and distributes only 2,200 volt energy. The system of connections throughout is based on the double-bus, double-switch scheme, with provision for disconnecting any oil switch for cleaning or repairs without interrupting the circuit.

XII. Development of Pennsylvania Water Power Company on Susquehanna River at Holtwood, Pa.

The dam for the McCall Ferry Station shown in Fig. 41, built across the Susquehanna River, is of solid concrete with an average height of 55 ft. and a width at the base of 65 ft. The down-stream face is provided with the usual curve, and to allow for expansion and contraction layers of compressible material are introduced at intervals of 40 ft. The dam impounds a body of water forming a lake above it about 8 miles in length, and in order to protect itself against claims for flooding property along the river, the company had to acquire large tracts of land on both sides of the river. In addition a wing dam having three submerged arches, through which the water enters the forebay, is built at right angles to the main dam, between which and a rock fill extending out for approximately 300 ft. at right angles to the shore, floating booms are provided so as to divert such ice and débris as are carried over the spillway. The submerged arches start at the junction of the power house and the dam and extend up-stream about 220 ft. The crowns of the arches are 2 ft. below low-water level, so that they are always submerged. The gap between the ends of the arch construction and the rock embankment is closed by the log booms, guided by concrete piers. Any ice which enters the forebay despite these safeguards, as well as ice which may be formed there, is diverted through ice shutes placed between the power house and the shore, with crests at the same elevation as the crest of the main spillway.

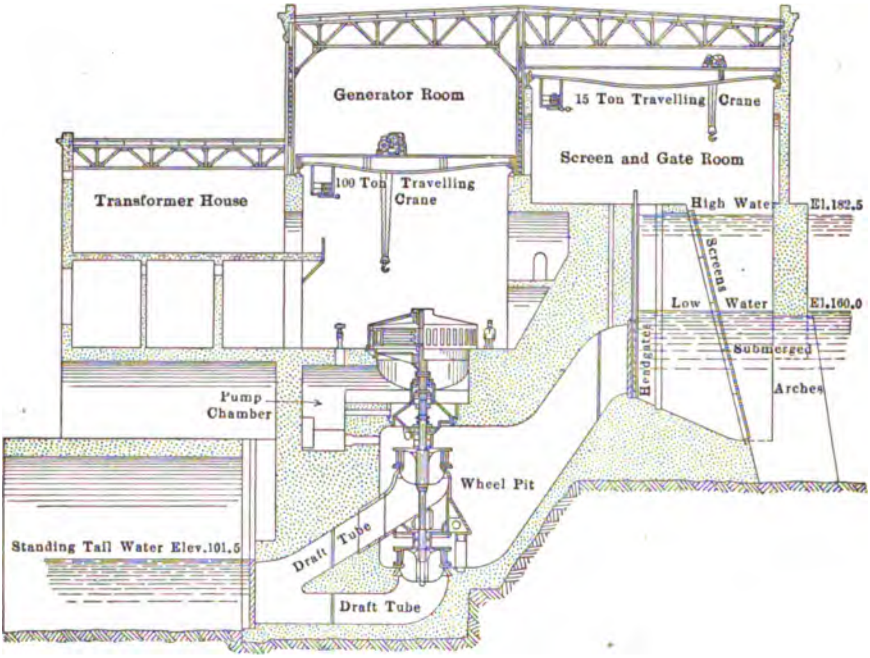


Fig. 41.—Hydroelectric Plant of Pennsylvania Water Power Company on Susquehanna River at Holtwood, Pa.

The hydraulic work is completed at this plant for a 135,000 hp. development. The completion of the power station only is required for the full installation. Eight units are installed, each consisting of vertical shaft, inward and downward flow Francis type I. P. Morris turbine rated at 13,500 hp. at 53 ft. head and 80 per cent. gate opening, direct connected to 11,000 volt, 25 cycle, three-phase generator. One General Electric 7,500 kw. generator is installed; four 10,000 kw. General Electric units and three Westinghouse units rated at 12,000 kw. The generators are Y connected and provided with a lead for grounding the neutral. Pneumatic brakes with brake bearing on the revolving field ring stops the machines. The total station rating in 1916 was 83,500 kw. The transmission voltage is 70,000 volts stepped up by 11,000 to 70,000 transformers with delta low and star high potential connections with neutral grounded. Aluminum cable conductors 300,000 c.m., 19 strand are used. The bulk of the energy is transmitted to Baltimore, Md., over 40 miles of transmission line. The station was built in 1910.—*Electrical World*, August 24, 1912.

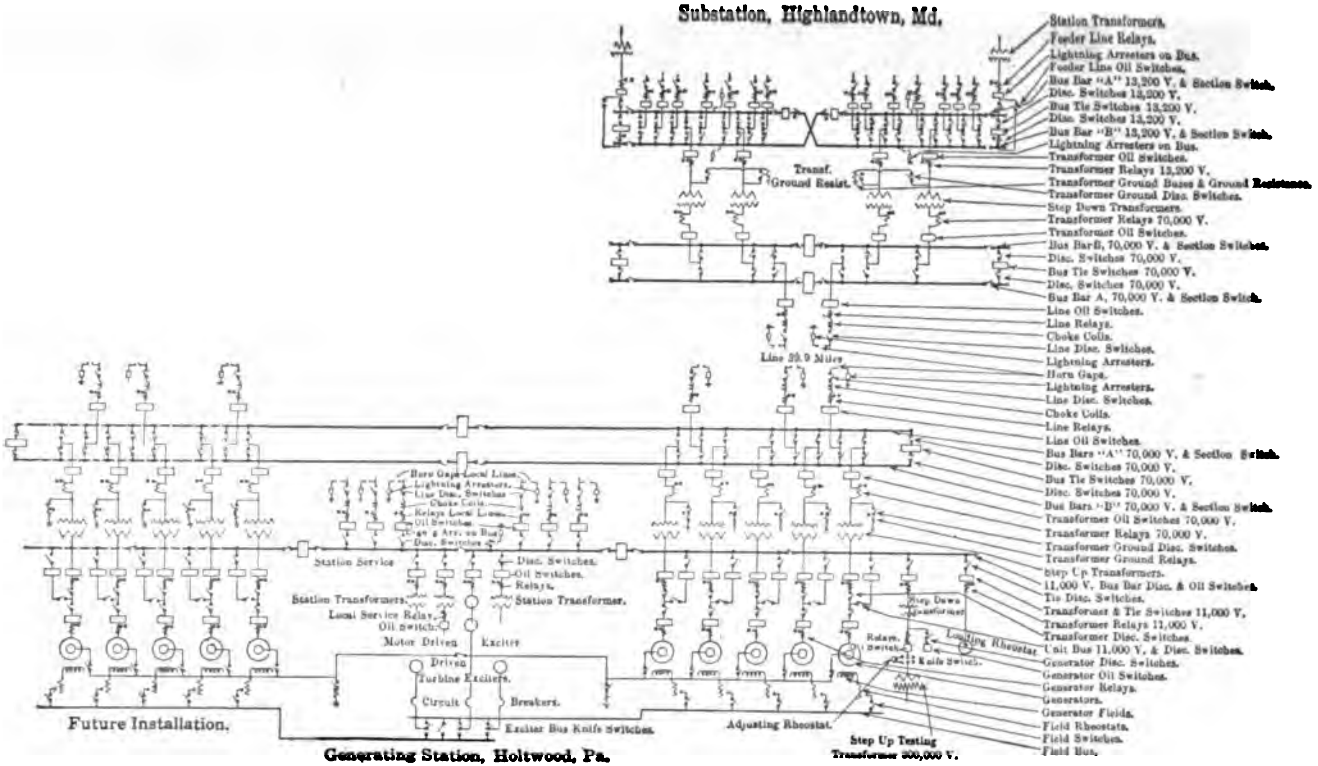

Substation, Highlandtown, Md.
Station Transformers.
Feeder Line Relays.
Lightning Arresters on Bus.
Feeder Line Oil Switches.
Bus Bar "A" 13,200 V. & Section Switch.
Disc. Switches 13,200 V.
Bus Tie Switches 13,200 V.
Disc. Switches 13,200 V.
Bus Bar "B" 13,200 V. & Section Switch.
Lightning Arresters on Bus.
Transformer Oil Switches.
Transformer Relays 13,200 V.
Transformer Ground Buses & Ground Resistance.
Transformer Ground Disc. Switches.
Step Down Transformers.
Transformer Relays 70,000 V.
Transformer Oil Switches.
Bus Bar B, 70,000 V. & Section Switches.
Disc. Switches 70,000 V.
Bus Tie Switches 70,000 V.
Disc. Switches 70,000 V.
Bus Bar A, 70,000 V. & Section Switch.
Line Oil Switches.
Line Relays.
Choke Coils.
Line Disc. Switches.
Lightning Arresters.
Horn Gaps.
Lightning Arresters.
Line Disc. Switches.
Choke Coils.
Line Relays.
Line Oil Switches.
Bus Bars "A" 70,000 V. & Section Switch.
Disc. Switches 70,000 V.
Bus Tie Switches 70,000 V.
Disc. Switches 70,000 V.
Bus Bars "B" 70,000 V. & Section Switch.
Transformer Oil Switches 70,000 V.
Transformer Relays 70,000 V.
Transformer Ground Disc. Switches.
Transformer Ground Relays.
Step Up Transformers.
11,000 V. Bus Bar Disc. & Oil Switches.
Tie Disc. Switches.
Transformer & Tie Switches 11,000 V.
Transformer Relays 11,000 V.
Transformer Disc. Switches.
Unit Bus 11,000 V. & Disc. Switches.
Generator Disc. Switches.
Generator Oil Switches.
Generator Relays.
Generators.
Generator Fields.
Field Rheostats.
Field Switches.
Field Bus.
Transf. Ground Resist.
Line 39.9 Miles
Horn Gaps Local Lines.
Lightning Arresters.
Line Disc. Switches
Choke Coils.
Relays Local Lines.
Oil Switches.
Gaps & Arr. on Bus.
Disc. Switches
Station Service
Disc. Switches.
Oil Switches.
Relays.
Station Transformers.
Station Transformer.
Local Service Relay.
Oil Switch.
Motor Driven
Exciter
Driven
Turbine Exciters.
Circuit
Breakers.
Exciter Bus Knife Switches.
Step Down Transformer
Loading Rheostat
Relays.
Oil Switch.
Knife Switch.
Adjusting Rheostat.
Step Up Testing Transformer 200,000 V.
Future Installation.
Generating Station, Holtwood, Pa.

Fig. 42.—Circuits of Holtwood Station Pennsylvania Water and Power Company with Transmission Lines and Substations

The Baltimore terminal station is in the suburbs at Highlandtown, Md. The generating station from its lines and substations serves railway, lighting and industrial loads.

The power house, gatehouse and transformer house was planned for ten units, including rheostat and switchboard galleries, compartments for transformers and other apparatus. All of the headworks, foundations, etc., are completed for a 135,000 hp. development, the only work required to prepare the power house for the full installation being an addition to the present superstructure. The initial installation consisted of six units.

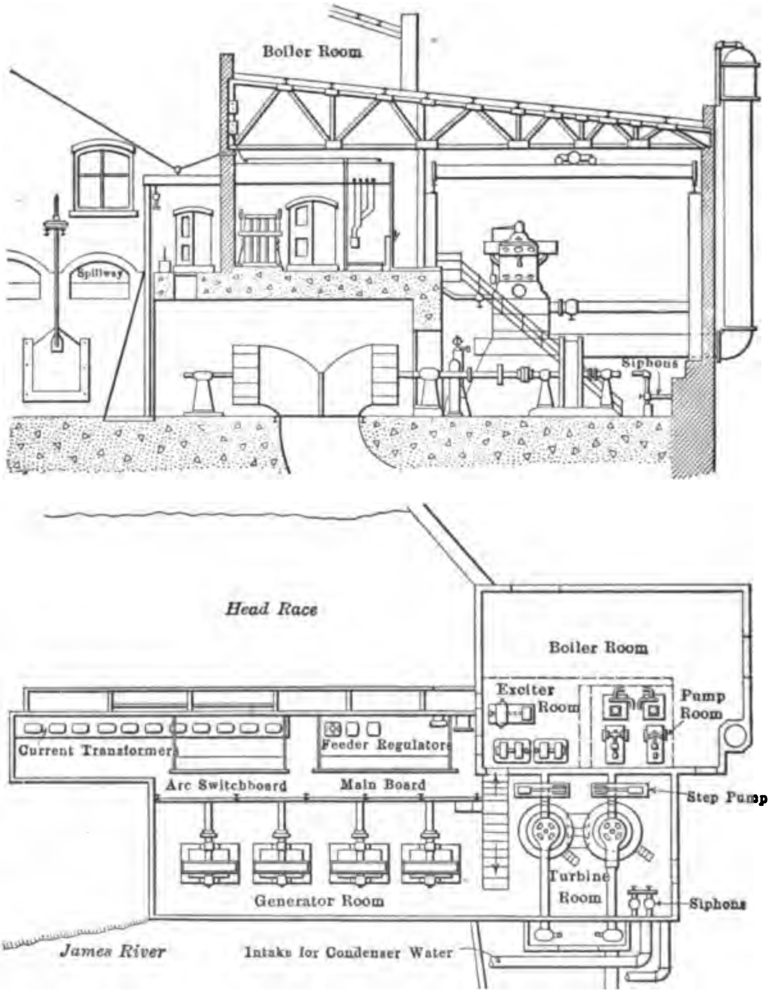


Fig. 43.—Plant on James River which Lights City of Richmond, Va.

This station contains four S. Morgan Smith 42 in. water wheels of the horizontal double runner type, each direct connected to a 425 kva. three-phase, 4-wire 4000/2300 volt, 60 cycle generator operated at 150 r. p. m. The operating head is 18 ft. The station also contains two turbo-generators rated at 1,000 kva. for operation during low water. The boiler and turbine room is a part of the station building. The plant was designed by E. W. Trafford superintendent and city electrician.—*Electrical World*, April 18, 1914.

Eight units are now (1916) in operation and have a combined rating of 83,500 kw. The generator voltage is 11,000 and the transmission voltage 70,000. The power house is 48 ft. wide and will be 500 ft. long inside when completed with a floor 14 ft. below the crest of the dam.

XIII. HYDROELECTRIC-STEAM PLANT ON JAMES RIVER, NEAR RICHMOND, VA.

The design of the plant shown in Fig. 43 was fixed to a certain extent by the foundation of an existing steam-turbine plant in which the hydraulic generating units are installed. Wherever possible the walls of the old building, which were of dressed granite and in excellent condition, were used. The building is constructed in the shape of an "L," with a length of 168 ft. and a width of 75 ft. Some excavation had to be done for the draft tubes of 6 ft. dimensions, which extended from the wheels under the building and at right angles to the river.

The dam is a monolithic concrete structure, its average height being 15 ft. The total length of the dam is 2,200 ft., extending into the stream, however, only about 400 ft. in an almost parallel course with the shore line. The dam does not reach across the river, as the rights extend only to the center line of the river. At the center it touches a small island-dam, which takes the other half of the river. The pondage is very small, being only about 13 acres, and the plant depends almost wholly upon the flow of the river, which averages about 2,500 second ft. At the intake of the head-race eight gates are provided completely to shut off and to regulate the water in the race. The length of the race from the plant to the head-gates is about 500 ft. The race level is the same as that of the openings, and the overflow goes over the dam crest. Trash racks are provided at the wheel-pit openings. There is also a drop-gate arrangement, consisting of heavy plates, for completely blocking individual pits in case repairs are to be made to the wheels.

At present there are four 42 in. wheels directly coupled to water wheel-type alternators. The 425 kva. alternators are of the three-phase, four-wire, 4,000/2,300 volts, 60 cycle, revolving field type and run at 150 r. p. m. The wheels operate under a normal head of 18 ft.

XIV. A 3,000 KW. DEVELOPMENT ON MENOMINEE RIVER IN MICHIGAN

The power station illustrated in Fig. 44 is constructed of monolithic concrete pillows and concrete blocks. Both the trash rack and the open flumes above the wheels are virtually set in the extended bed of a canal, the tailrace extending under the power house and transformer room. The 3 ft. solid-concrete bulkhead wall on the up-stream side of the generator room withstands the pressure of the 26 ft. head of water in the canal.

The alternating current generating equipment of the station consists of three 1,500 kw., three-phase, 60 cycle alternators each driven by four 52 in. waterwheels connected to an open flume and operating under a 26 ft. normal head. The normal rating of each set of wheels is 1,900 hp. All of the machines operate at 150 r. p. m. and are controlled by oil governors. Oil pressure for these governors is furnished by pumps belted to the generator shafts. Duplicate exciters rated at 100 kw., 125 volts, and 350 r. p. m., are installed in the center of the station. These units are driven by two 22 in. waterwheels also controlled by oil-pressure governors. Mechanical governors are generally deemed sufficient for such exciter units, but in this case for particularly good regulation oil governors were chosen.

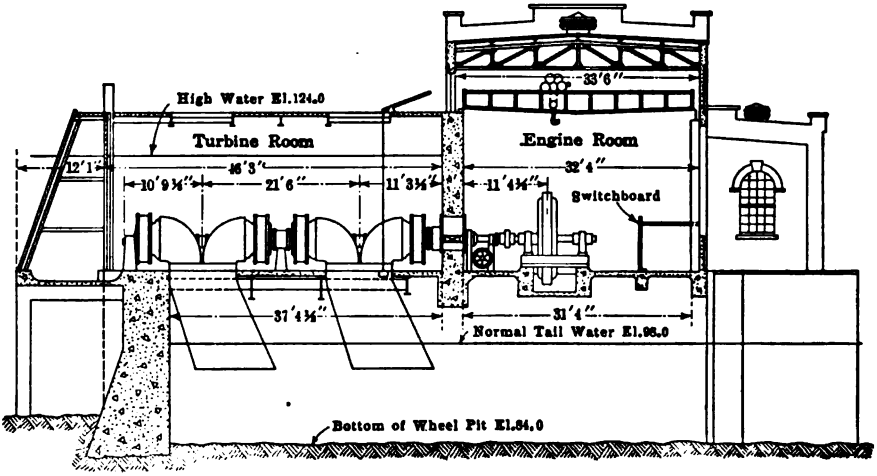


Fig. 44.—Rapids Power Station of the Menominee and Marinette Light and Traction Company on Menominee River in Michigan

This station contains two 1500 kw. three-phase, 60 cycle Westinghouse generators, driven by 52 in. Dayton Globe water wheels operated under 26 ft. normal head. The normal rating of each of the wheels is 1,900 hp. An additional unit drives a 1,500 kw. General Electric generator. The transmission voltage is 33,000. The plant was placed in operation August, 1910.—*Electrical World*, January 17, 1914.

As a means of stopping the generators (1,500 kw.), which when running light will continue to revolve under their own momentum for several hours, a galvanized iron tank has been placed behind the switchboard and connected as a water rheostat. By loading the three phases of a unit with this resistor, a machine may be brought to rest in a very few minutes.

XV. Station on Maumee River Near Toledo, Ohio

The generating station building in Fig. 45 is 110 ft. by 30 ft., with concrete foundation carried to bed-rock. The walls are of brick, with steel trusses supporting the roof. The forebay extends 800 ft. from a canal to the river bank and is approximately 94 ft. wide at the surface, its banks sloping to a width of 40 ft. to 60 ft. at the bottom, at an average depth of

14 ft. At its end, where the water enters the flumes, there is a concrete retaining wall containing three gates which are raised and lowered by hand-operated worm-gear. In front of the gates is located an inclined steel-bar trash rack carried on I-beams. The penstock flumes leave this concrete wall, into which they are suitably anchored at different angles, diverging to accommodate the center-line distances of the side-entrance water wheel cases in the power house below. Each penstock is approximately 230 ft. long and 7 ft. 6 in. in diameter, the upper sections being built of $\frac{5}{16}$ in. boiler plate while in the lower portions this thickness is increased to $\frac{7}{16}$ in. The flumes have a slope of 1⅝ in. per foot and are carried at approximately 12 ft. intervals on concrete piers. At the top of the hill, near the gates, where the tubes pass under a country boulevard, the flumes are protected by a reinforced concrete wall arched to carry the earth load.

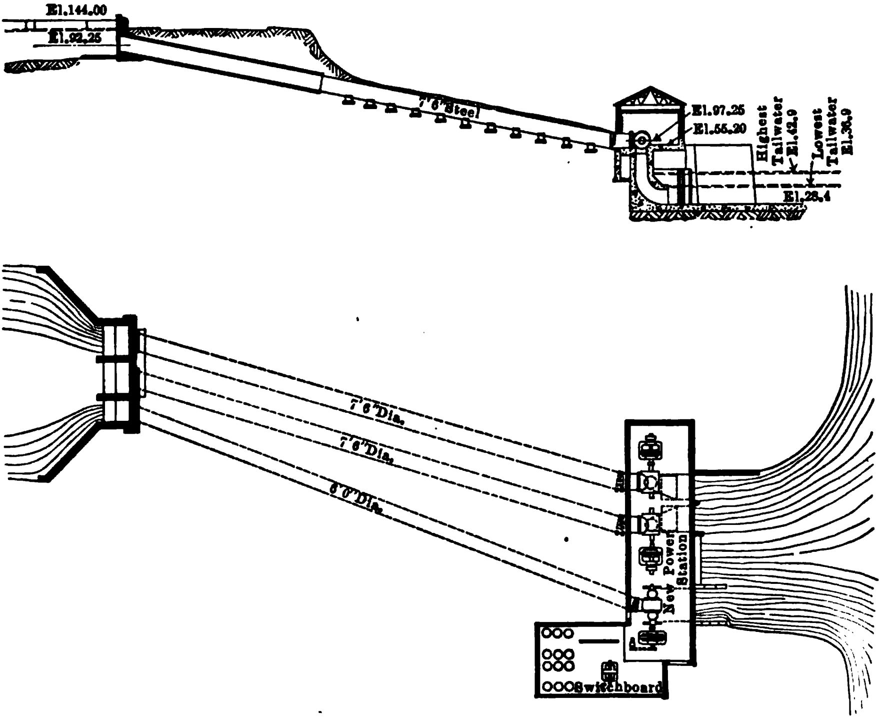


Fig. 45.—Station of Maumee Valley Electric Company Near Toledo, Ohio

This station contains two double runner 26 in. and one single runner 26 in. water wheels which operate under a head of 62 ft. The double runner units are of horizontal pattern, with side entry and center discharge of Allis Chalmers design. The single runner is of Leffel design, double discharge. The former drive at 400 r.p.m. three-phase, 60 cycle 2300 volt 190 amp per phase generators. The latter wheel drives a 115 amp per phase generator of same design. The plant furnishes energy to Toledo over an 8 mile 13,200 volt transmission line. R. R. Livingston, consulting engineer New York City, designed the plant and construction was in charge of W. P. Wallace, superintendent of the company.—*Electrical World*, March 2, 1911.

Generating Units.—The initial equipment in the power house comprised two 26 in. double-runner and one 26 in. single-runner water wheels. They are of the horizontal type, with side entry and center discharge, and each drives, at 400 r. p. m., a 2,300 volt, 60 cycle, three-phase alternator delivering 190 amps. per phase. The individual exciters are mounted on extension shafts. The speed of these units is controlled by oil-pressure governors, with oil-pumps belted to the shafts. A small motor manipulated from a double-throw switch on the switchboard enables the setting of the governors to be controlled by the operator. The 26 in. single-runner double-discharge turbine drives an alternator similar to the other machines, but delivers 115 amps. per phase. The average hydraulic head is 62 ft.

Draft Tubes.—In the concrete foundations carrying the water wheels are moulded the draft tubes to discharge the water leaving the turbine units. Owing to the attention given to the draft tubes the normal vacuum has approached the theoretical, there being a hydrostatic head of 21 ft. from the center of the turbine to the surface level of the tailrace water.

XVI. HYDROELECTRIC PLANT ON OCMULGEE RIVER NEAR JACKSON, GA.

The ultimate rating of the development shown in Fig. 46 is 33,000 hp. maximum. The initial installation consisted of four 3,000 kva., 2,300 volt, 60 cycle generating units direct-driven by water wheels under a head of 100 ft. The generating station is located at an abrupt slope of the river, and at the site of the dam the valley is extremely narrow. The west bank of the river rises to a height of 120 ft. at a distance of only 150 ft. from the edge of the channel. The opposite bank of the river is less steep, although the abutment extends only 600 ft. from the water's edge. A total length of 1,700 ft. was sufficient for closing the valley and the securing of 100 ft. head at the plant site. The dam is a monolithic concrete structure, having a total length of 1,050 ft. between abutments, with a 750 ft. spillway extending from the east abutment to a point near the center of the original river channel. The power house was built between the end of the spillway and the west shore of the stream, the down-stream face of the dam forming in part the rear wall of the generating station. The location beneath and at one face of the dam resulted in a simple hydraulic design.

Penstocks.—The river serves as its own forebay, and no canal, flume or elaborate penstock construction was necessary. Each unit is supplied with water by a short penstock, 12 ft. square, with flattened corners, leading through the dam to the wheelpit of the station, the wheels being of the central-discharge type with short draft-tube connections leading into the tailrace. The draft tubes are elliptical in section and are 11.5 ft. by 15 ft. in dimensions at the discharge end. The discharge is carried directly downward from the wheels and deflected into the tailrace by an easy curve at the bottom of the tubes, so that the minimum amount of retardation is experienced through friction. It was the aim of the designers of this plant to avoid reducing the wheel efficiency by leaving water passages in service where sharp corners or unsatisfactory curves may cause a partial impedence to the flow.

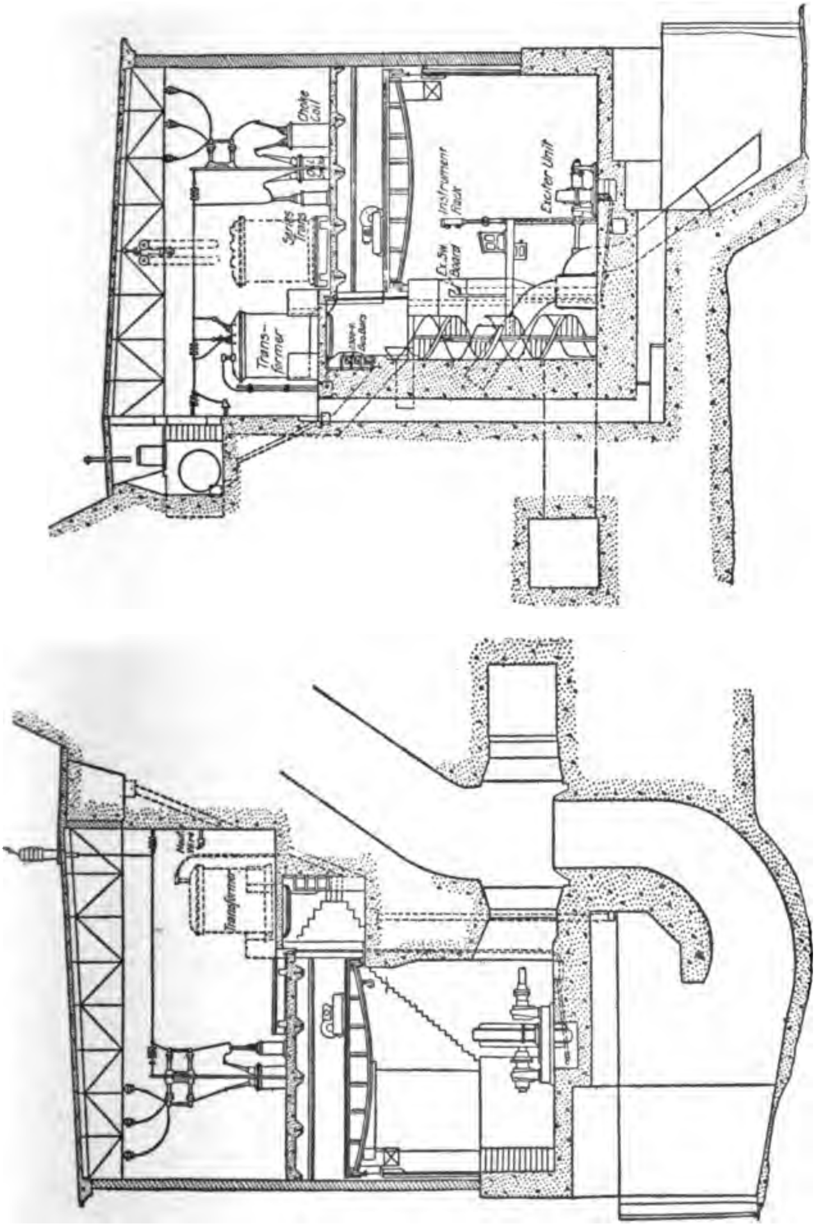


Fig. 46.—Station of Central Georgia Power Company near Jackson, Ga., on Ocmulgee River

This station provides for six generating units consisting of 5,500 hp. S. Morgan Smith wicket gate turbines, operating under a 100 ft. head and direct connected to 3,000 kva. 2300 volt, 60 cycle Westinghouse generators. The initial installation included four of these units. The station furnishes energy to transmission lines to Atlanta, Ga., and Macon, Ga., distances of about 100 and 50 miles respectively. The transmission voltage is 66,000. At Atlanta the lines connect with the system of the Georgia Railway and Power Company. Lockwood Green & Company were consulting engineers and J. G. White & Company engineers and constructors.—*Electrical World*, April 27, 1911.

Power House.—The power house is a brick and steel building 200 ft. by 45 ft. and two stories in height. The outer and division walls are of brick and are 20 in. thick at the first story and 16 in. thick at the upper story. Brick pilasters are provided for traveling-crane service. The floors and roof are of steel-beams and concrete-slab construction, the roofing being five-ply tar and gravel. The station cornices are of concrete and the windows are of wooden frame, sash and clear-glass construction. The downstream side of the station is on a line with the bed of the dam and its profile conforms to the slopes of the dam. As a result the upper floor is stepped back one bay beyond the lower floor. The basement of the plant is devoted to draft tubes and tailrace discharge outlets, and is of concrete construction throughout. Separate discharge outlets are provided for each hydraulic unit.

Generating Units.—The generating equipment of the plant consists of four 3,000 kva., 2,300 volt, three-phase, 60 cycle alternators, each direct-connected by a horizontal shaft to a water wheel operating at 300 r. p. m. There are two exciter sets in service, one being driven by a small water wheel and the other by a motor. The exciters run at 550 r. p. m. and deliver direct current at 250 volts for station lighting as well as for field excitation. The main generating units are of the revolving field type. The water wheel governors are mounted in a recessed portion of the generating-room wall on the same floor level as the alternators. On the dam side of the building is located a switchboard gallery of concrete construction, the platform being carried on steel posts set into the generating-room floor. The entire operating-room is served by an electrically driven crane with cab for controller equipment. Behind the switchboard is a circular staircase leading from the main floor to the gallery and second floor. All the transformers and high voltage equipment of the station is located on the upper floor of the building, where ample space has been provided for safe operation.

The transformer equipment consists of four 3,000 kva. three-phase, 2,300/66,000 volt units mounted on the floor of the second story. Their primaries of 2,300 volts are connected in delta and the high voltage secondaries are connected in star, with a grounded neutral.

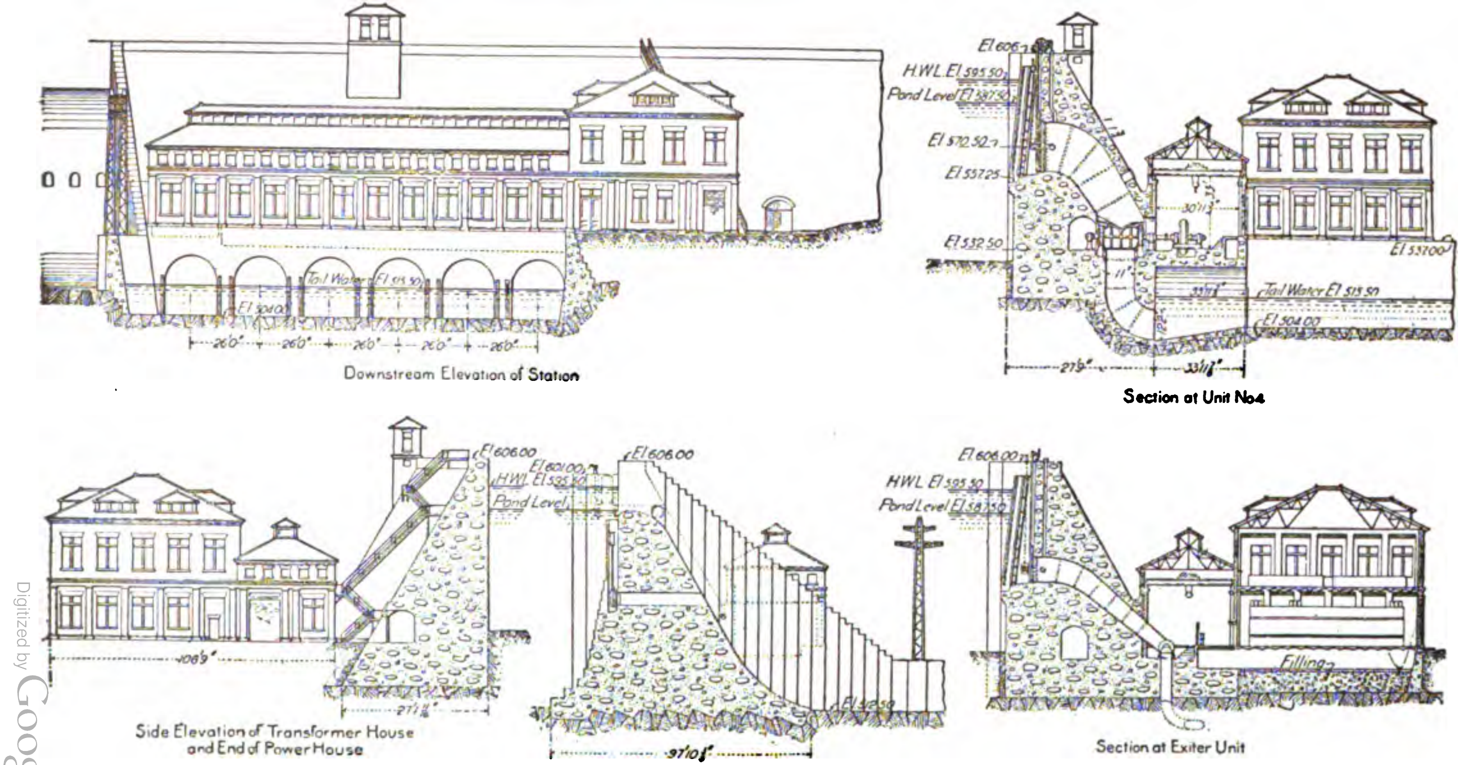
XVII. NINETY-NINE ISLAND STATION OF SOUTHERN POWER COMPANY ON BROAD RIVER NEAR BLACKSBURG, S. C.

Growth of Southern Power Company's System.—The Southern Power Company operates five hydroelectric plants on the Catawba River in North and South Carolina besides the 99 Island station on the Broad River in South Carolina, and three steam stations of 10,000 hp. each. The combined rating of the six water power plants is something more than 125,000 kw. The Catawba station, rated at 10,000 hp., was built first. It was completed in the spring of 1904 and in 1905 the Southern Power Company was organized for the purpose of taking over this plant and developing water powers on the Catawba and Broad Rivers. The great system of this company from this time rapidly sprung into existence. At this time the transmission system in the Carolinas consisted mainly of 13,000 volt lines from the Catawba station to Rock Hill 6 miles, to Clover 18 miles and to Charlotte, 23 miles in North Carolina. In 1907 however, the Great Falls station of 32,000 hp. was placed in operation and 200 miles of 50,000 volt transmission line, in the spring of 1909 the Rocky Creek station of 32,000 hp. was completed and an additional 200 miles of 50,000 volt transmission line, and in the autumn of 1909 another 250 miles of 100,000 volt transmission line was placed in service. A little later another circuit was strung on the 100,000 volt towers and 140 additional miles of two circuit 100,000 volt line completed making a system operating 1,380 miles of three-phase transmission line all built in a period of five years. In the spring of 1910 the 99 Island station rated at 24,000 hp. was completed. This gave the company a total capacity in four water power plants of 73,500 kw. The building of additional stations was not called for aside from standby steam plants for low water conditions until 1915, when a 30,000 hp. station at Lookout Shoals on the Catawba River was placed in service. There was under construction at the same time a 30,000 hp. station on Fishing Creek just above the Great Falls station on the Catawba which was placed in service in 1916.

During the period that the Southern Power Company was building transmission lines in all directions in the south central part of North Carolina and the northwestern section of South Carolina there were under construction twenty-five 10,000 volt; thirty-two 50,000 volt; and eighteen 100,000 volt outdoor substations ranging in size from 300 kw. to 28,000 kw. with secondary voltages of 550, 2,200, 11,000 and 44,000 volts. A large part of the energy from the system is used by cotton mills, by towns and villages for light, power and street railway service.

The Southern Power Company in 1916 operated over 1,600 miles of transmission lines, more than 100 substations aggregating 250,000 hp. In addition the company controls the Southern Public Utilities Company which retails energy purchased from the transmission system and operates other small properties.

99 Island Station.—This station is in a way typical of the character of station designed and built by the Southern Power Company. It is comparatively recent, being the last of the group built from 1906 to 1910. The development of the site embraced the construction of a spillway 891.12 ft. long extended by bulkheads about 140 ft. on one side and 600 ft. on the other. The spillway was designed to afford a head of 72 ft. The intakes, cases and draft tubes for the turbines were built into the masonry of the



Downstream Elevation of Station

Section at Unit No.4

Side Elevation of Transformer House and End of Power House

Section at Exiter Unit

Fig. 47.—General Features of Power House and Dam of Ninety-nine Islands Development of Southern Power Company

600 ft. bulkhead. The power house is a one-story structure about 220 ft. by 36 ft. flanked on one end by a building 63 ft. by 70 ft. which contains switching and transformer apparatus and offices. These buildings are framed in steel and enclosed with brick curtain walls. The floors are of concrete laid over arched corrugated steel plates sprung between I-beams.

Six 5,200 hp. water wheels of the top inlet, center discharge, twin runner swivel gate, horizontal pattern are direct connected to six 3,000 kw. 2,200 volt, three-phase, 60 cycle generators operated two in parallel with a bank of three transformers. There are three banks of transformers each made up of three 2,000 kva. units oil insulated and water cooled, delta connected to step up the voltage from 2,200 to 44,000 volts. The station is practically the same in equipment as the Rocky Creek station which was completed about a year before. The high tension leads are carried through open wells into the second story of the station where are mounted the choke coils, switches and other high tension apparatus. Solenoid and gravity operated non-automatic 1,200 amp. circuit breakers were used for generators; 2,000 amp. 2,200 volt and 45,000 volt non-automatic breakers for sectionalizing; 2,000 amp. 2,200 volt and 45,000 volt automatics for transformers with 45,000 volt inverse time limit relays for feeders. The electrical installation was made by the Westinghouse Electric and Mfg. Company. The turbines were furnished by the Allis Chalmers Company. The station was planned and executed under the direction of W. S. Lee chief engineer of Southern Power Company and C. A. Mees, designing engineer.—*Engineering Record,* April 2, 1910.

XVIII. DEVELOPMENT OF GEORGIA-CAROLINA POWER COMPANY ON SAVANNAH, GA., NEAR AUGUSTA

Nine miles above Augusta, Ga., on the Savannah River, at the mouth of Stevens Creek, a 13,500 kva. hydroelectric plant has been constructed from which energy is transmitted at 44,000 volts to a substation at Augusta, Ga. This station is tied in with a 4000 kva. hydro-steam plant at Augusta and a 25 mile transmission line extending to Clearwater and Aiken, S. C. All of the energy is supplied to the Augusta-Aiken Railway & Electric Corporation, which in turn sells part for industrial power and lighting purposes. Sufficient water power is available in the Savannah River at the plant site to develop 31,250 hp., so the wheel pits have been constructed with this ultimate development in view. The additional 15,625 hp. in equipment will not be installed until the market for electrical energy warrants it.

Dam.—The dam, which is of solid cyclopean concrete 2700 ft. long and 30 ft. above bedrock, on the average, impounds water for 13 miles up-stream and provides a 27-ft. head normally. An additional head of 4 ft. can be obtained with flashboards. The spillway, which has an ogee contour and is 2,000 ft. long, is designed to discharge 450,000 cu. ft. of water per second.

With this discharge rate the maximum depth over the spillway is 14 ft. 6 in. Built in the dam are five 8 ft. by 8 ft. sluicegates, each of which will carry off 2,000 cu. ft. of water per second. Between the spillway and the power house, which is on the Georgia side of the river, are 30 ft. by 150 ft. navigation locks. The gates for filling and emptying the locks, as well as the sluicegates, are operated by hand at the present time, but provisions are made for motor operation.

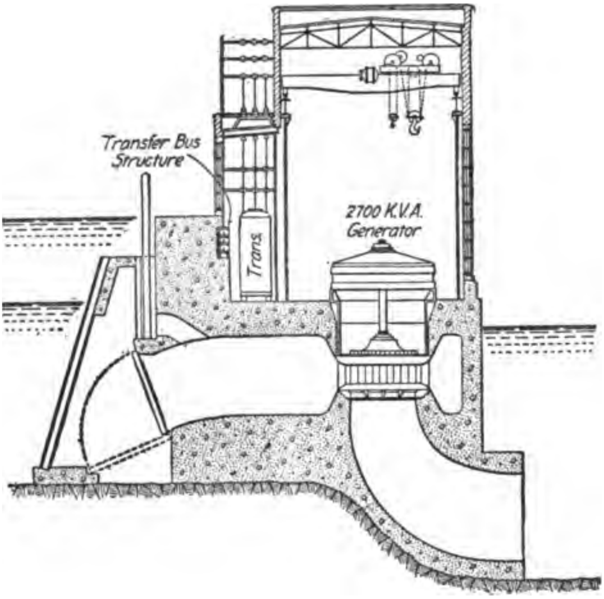


Fig. 48.—Power House of Georgia-Carolina Power Company's 13,500 Kva. Development on the Savannah River

This station contains five I. P. Morris Francis-type, vertical-shaft, single runner turbines, each rated at 3,125 hp. and direct connected to a three-phase, 2,300 volts, 60 cycle, 2,700 kva. (maximum) Westinghouse generator. The turbines operate under 27-ft. normal and 31-ft. maximum head. The station is tied in with a 4000 kva. hydro-steam station at Augusta, Ga., and all energy is supplied to the Augusta-Aiken Railway and Electric Corporation which retails it for industrial power and lighting purposes. Sufficient water-power is available in the Savannah River at the plant site to develop 31,250 hp., so that the wheel pits were constructed with this ultimate development in view. The transmission voltage is 44,000. Wide base and latticed steel towers are used. The system was designed and constructed by the J. G. White Engineering Corporation, New York City.—*Electrical World*, November 20, 1915.

Generating Units.—The power-house substructure will accommodate ten generators in two groups, between which are the exciters and main switch board. Only the five generators nearest the shore and the exciters have been installed so far, with their protecting superstructure. The remainder of the electrical equipment, including transformers, main buses and oil switches, is installed in a bay extending along the up-stream side of the power house. Rheostats, control-circuit battery, station auxiliary bus and transformers and one lightning arrester are situated on a gallery back of the switchboard. Each of the three transformers provided is capable of caring for the energy delivered by two generators. A 50-ton motor-operated crane runs over the main floor. Anchor rings in the wall and floor enable this crane to be used in moving the transformers.

The prime movers are I. P. Morris Francis type vertical-shaft single-runner turbines rated at 3,125 hp. at 75 r. p. m., with a head of 27 ft.

Each is directly connected with a three-phase, 2300 volt, 60 cycle, 2700 kva. (maximum) Westinghouse generator. The turbines have guaranteed efficiencies of 84 per cent. at full load, 86 per cent. at 2950 hp., 81 per cent. at three-quarters load and 72 per cent. at half load. With full load and 75 per cent. power-factor, the generators are guaranteed not to increase more than 50 deg. C. in temperature after twenty-four hours' operation.

XIX. Proposed Outdoor Hydroelectric Station for the South

Although outdoor designs of switching and transformer stations are quite common nowadays, an outdoor design of generating station has yet to be constructed. Such a design has been considered at least in one case for the South, the features of which are shown in Fig. 51. The design called for a rating of 50,000 kva. and the estimated cost of the complete development following standard lines was $70 per kilowatt. Of this amount the power house represented $84,000.

In this projected installation the generators and transformers are all outdoors. The control boards and exciters are installed in the structure over the tailrace, where provision was also made for repairing equipment. The power site having passed into other hands, the installation depicted herewith was not made. A simpler design for an outdoor generating station of much greater rating has since been made for a development, of a different nature, the energy

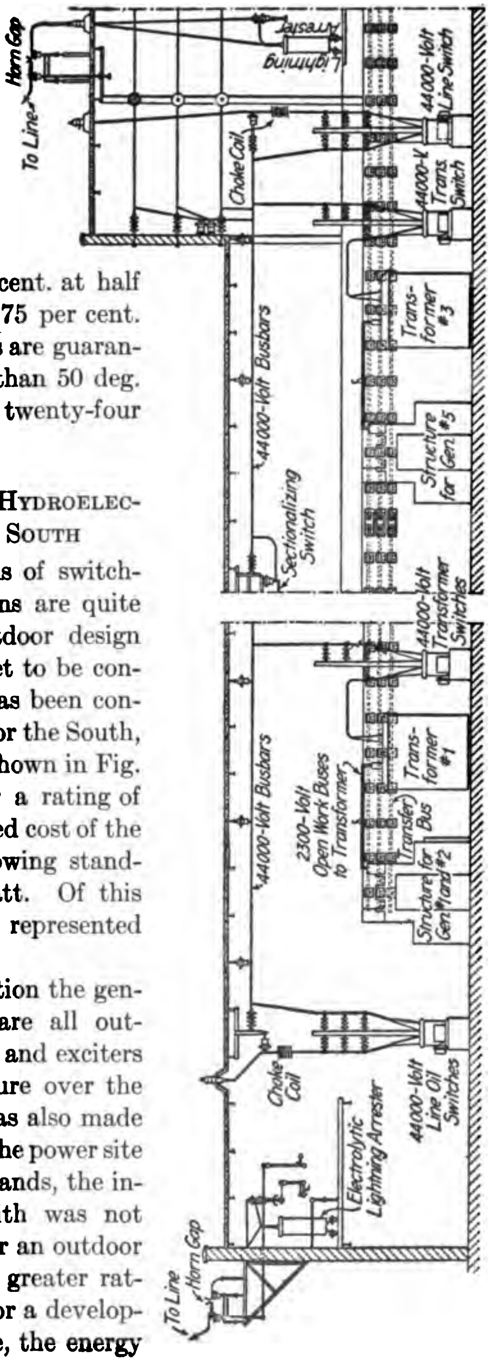


Fig. 49.—Bus Arrangement and Switching Connections in Station of Georgia-Carolina Power Company. (See descriptive title under Fig. 48)

from which would be used in carrying on electrochemical processes. The design calls for the largest water wheel ever built.—*Electrical World*, Sept. 25, 1915.

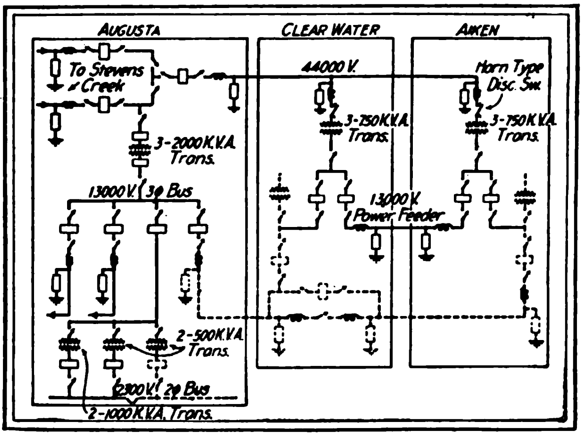


Fig. 50.—Methods of Connecting Switches and Transformers in Substations of Georgia-Carolina Power Company Served from 44,000 Volt Transmission Line

[See descriptive title under Fig. 48.]

XX. Hydroelectric Plant of Eastern Michigan Edison Company on Huron River, near Ann Arbor, Mich.

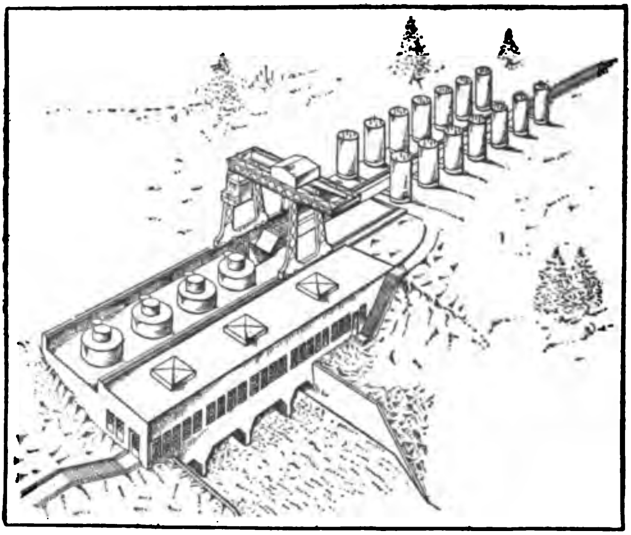


Fig. 51.—Perspective View of 50,000 Kva. Outdoor Type Generating Station

The Barton water-power plant of the Eastern Michigan Edison Company, near the city of Ann Arbor, Mich., is one of a series of low-head power plants contemplated by this company along the Huron River. The ultimate development will probably include nine similar plants, varying in head from 14 ft. to 32 ft. and utilizing a total fall of about 215 ft. This plant has a turbine rating nearly twice the average annual or equalized flow of the river, notwithstanding the fact that there is no artificial storage of flood waters above the site. This large turbine rating is warranted in this case because the Eastern Michigan Edison Company operates one steam and four hydraulic generating stations and is connected by duplicate

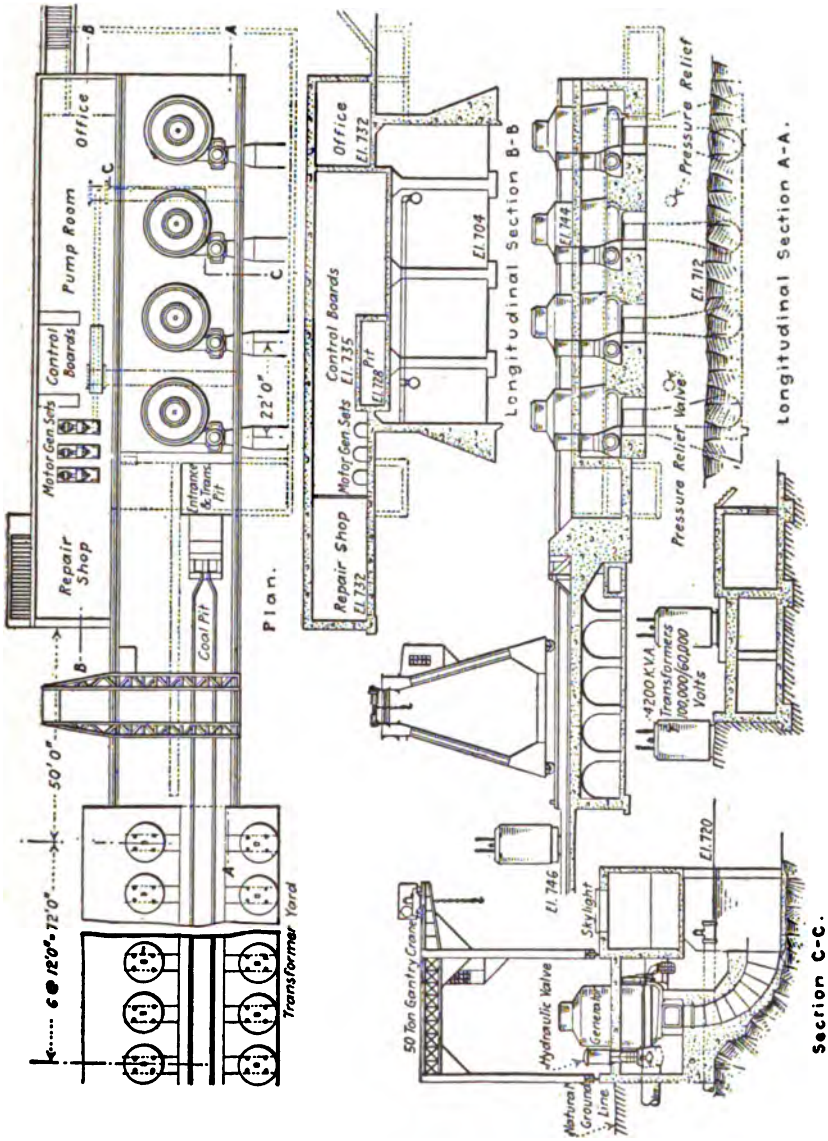


Fig. 52.—Plan, Longitudinal Sections and Cross-sections of Generating Station and Transformer Yard of Outdoor Hydroelectric Installation in Fig. 51

transmission lines with the large steam stations of the Detroit Edison Company. The relatively small total rating of all the generating plants of the Eastern Michigan Edison Company in comparison with the Delray and Conners Creek steam plants of the Detroit Edison Company allows the hydraulic stations to contribute power to the system at such times and in such amounts as they are able to produce at their best efficiency. The result is that water is wasted over the spillway of the Barton dam only in times of considerable floods, which last during an average year less than two weeks. In other words, excess machine capacity, in conjunction with a large distribution system, has made possible an economical water utilization that is sometimes accomplished by extensive storage reservoirs in the head waters.

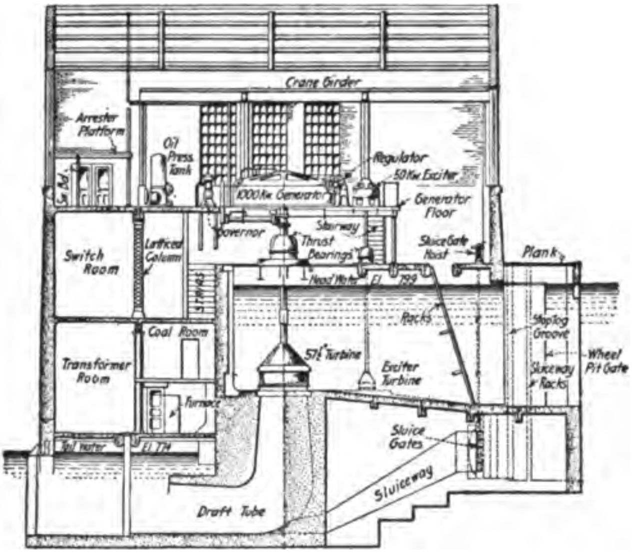


Fig. 53.—Station of Eastern Michigan Company on Huron River near Ann Arbor, Mich.

This station is one of four plants on the Huron River which serve as auxiliary stations to the Delray and Conners Creek stations of the Detroit Edison Company. The station contributes power to the system at such times and such amounts as can be used most economically. One vertical 68 in. turbine drives a 1000 kw. generator and another 57.5 in. turbine drives a 500 kw. generator, so that the station can be operated efficiently over load ranges from 250 kw. to 1500 kw. The turbines operate under a normal head of 20 ft. The construction cost per installed horse power of main turbines was $98.20 or $135 per kw. of generating equipment. The plant was designed and its construction was supervised by Gardner S. Williams, Ann Arbor, Mich. The electrical equipment was furnished by the General Electric Company and the hydraulic equipment by the Allis Chalmers Company.—*Electrical World*, December 25, 1915.

Power House and Equipment.—A longitudinal section of the power house is shown in Fig. 53. The building houses two main units, one a 68 in. turbine directly connected to a 1000 kw. generator, the other a 57½ in. turbine directly connected to a 500 kw. generator. Units of different sizes rather than two alike were installed to increase the plant efficiency. Thus high efficiency is had over a range of load from 250 kw. to 1500 kw. Between the two main units transversely, and up-stream from them, is the exciter unit, which consists of a 16 in. turbine and a 50 kw. exciter. All three are vertical units, the turbines being set in open-scroll-case wheel pits. The larger wheel pit is 16 ft. 3 in. and the smaller 10 ft. 3 in. wide, dimensions which keep the approach velocities down to about 2 ft. per second at maximum capacity. The turbines are set over concrete draft tubes which discharge the water into the tailrace at a velocity of about 3 ft. per second.

Among the unusual features of the power house are the two sluices which take water from the pond up-stream from the turbines and discharge it into the draft tubes. During the period of construction these sluices were used to carry the low-water flow of the river, and in the completed structure they afford a means of readily lowering the pond whenever desirable. Each sluice is controlled by a cast-iron sluicegate operated from the thrust-bearing floor. During the flood season of the year the sluices are also used to assist in regulating the pond level, and the discharging of the water into the draft tubes results in an increase of the power output of the turbines, compensating in a large measure for the decreased output due to rise of the tailwater level.

Transmission and Switching Arrangements.—The generator voltage is 2,300, and is stepped up to 23,000 volts for transmission. Both high-tension and low-tension switches are installed in the switch room directly below the switchboard and are manually controlled from the board. The switch room has a clear height of 16 ft. and oc-

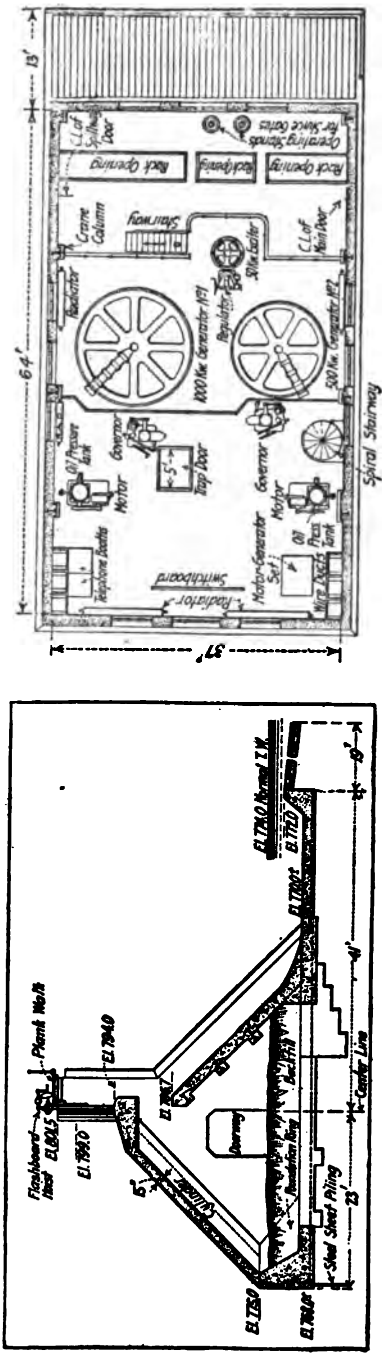


Fig. 54.—Construction of Multiple-Arch Dam and Arrangement of Generators, Exciters, Oil Governors and Control Apparatus at Eastern Michigan Company's Plant

cupies the down-stream third of the structure immediately below the generator floor and behind the wheel pits. Here are also the house-service transformers and main house-distribution panel.

Below the switch room is the transformer room, containing two banks of oil-cooled 2,300/23,000 volt, sixty cycle transformers of 1000 kw. and 600 kw. rating each. The window openings in this room are the full height of the room and are closed with galvanized-steel louvers with steel inside doors.

XXI. The 20,000 Kw. Development of Wisconsin River Power Company at Prairie du Sac, Wis.

The hydroelectric plant of the Wisconsin River Power Co., at Prairie du Sac, Wis., has the two specially interesting features of being built upon a deep sand foundation and having the crest of its dam formed by a series of large Tainter gates. The work comprises a power house 329 x 145 ft. at the west side of the river channel, a hollow concrete dam 1,000 ft. long and an earth embankment extending 1,700 ft. beyond the east end of the dam. Between the power house and the dam are a log chute and a navigation lock 35 by 170 ft.

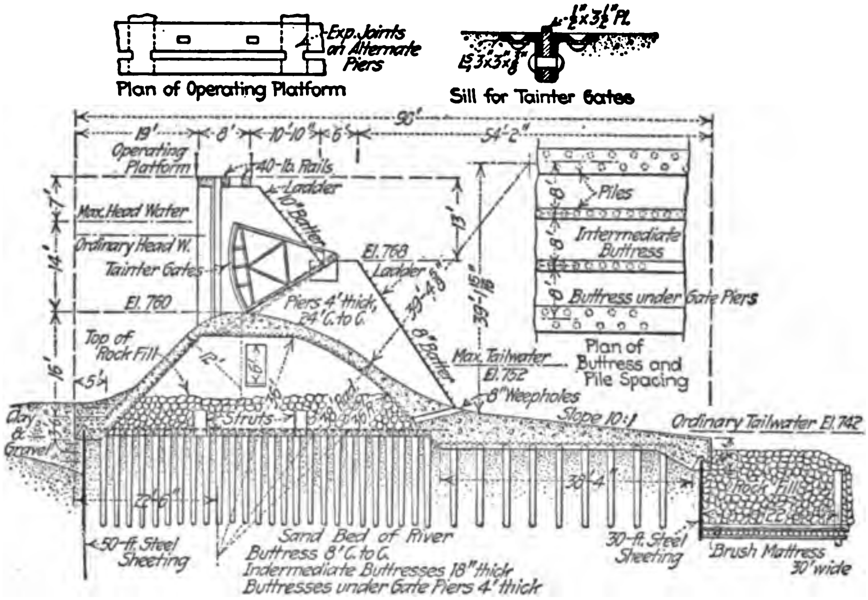


Fig. 55.—Section through Hollow Concrete Dam Built on Sand Foundation

Dam.—The dam is of the hollow concrete type, with interior buttresses and a long apron on the down-stream side. The crest is formed by a row of Tainter gates 14 x 20 ft. The buttresses are spaced 8 ft. c. to c., and between them are two lines of reinforced-concrete struts. Each third buttress is 4 ft. thick and is carried up as a pier to support the gates and operating platform. The intermediate buttresses are 18 in. thick and are entirely within the dam. All the buttresses have openings 3 x 6 ft. connected by a concrete-slab footwalk for inspection purposes. The sand beneath the dam is confined between two lines of steel sheetpiling—a line of 50-ft. sheeting under the up-stream face and a line of 30-ft. sheeting under the end of the apron. A filling of boulders and loose rock is placed inside the dam, and a clay and gravel fill is placed above the up-stream line of sheeting. Special provision is made against erosion below the end of the concrete apron. A heavy mat 30 ft. wide is laid against the down-stream sheeting, at a depth of about 15 ft., and is covered with a fill of heavy rock.

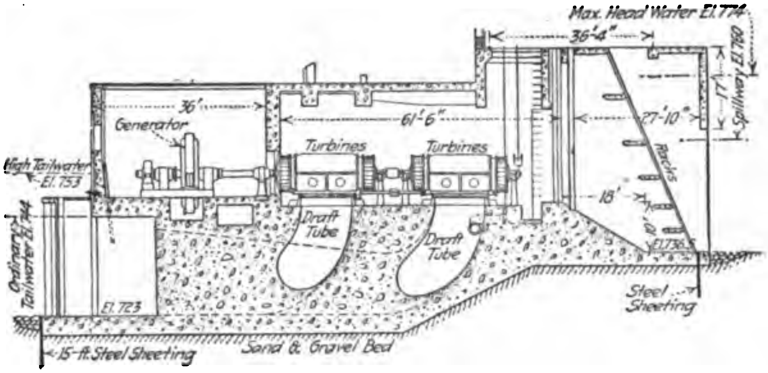


Fig. 56.—Hydroelectric Station of Wisconsin River Power Company on Sand Foundation

The power house substructure is of reinforced concrete supported on round piles spaced 4.5 ft. center to center. The entire power house area 329 ft. by 145 ft. is inclosed with steel sheet piling. The station was built in 1914 and after two years of operation no settlement or cracks have been noticed. The layout provides for eight 2500 kw. generating units six of which were included in the initial installation. Each unit consists of a turbine having four 64 in. wheels on a single line of horizontal shafting operating under a head of from 22 to 34 ft. The unit under maximum head develops 4000 hp. Each turbine set is connected to a 2500 kw. generator two being 60 cycle and four 25 cycle machines. The plant was designed and built under the direction of Prof. D. W. Mead and C. V. Seastone of Madison, Wis., as chief engineers of the Wisconsin River Power Company, R. G. Walker was resident engineer in charge of construction. The contractor for the entire construction of the dam, power house and lock, including the placing of the steel Tainter gates and the lock gates, was James O. Heyworth, of Chicago. The Tainter gates were built by the Lakeside Bridge and Steel Co., of North Milwaukee, Wis. The steel gates for the lock were built by the Federal Bridge Co., of Waukesha, Wis. The turbines and generators were built by the Allis Chalmers Co., of Milwaukee, Wis.—*Engineering News*, June 15, 1916.

Power House.—The power house is of reinforced concrete supported on round piles spaced 4.5 ft. center to center. The entire area 329 x 145 ft. is inclosed with sheet-steel piling which is 50 ft. long in the upper line, 15 ft. in the lower line and 40 ft. in the line between the power house and lock. An intermediate line of 15 ft. sheeting was driven about 50 ft. below the upper line. The draft tubes are of special design, each unit having two separate draft tubes extending to within 25 ft. of the down-stream face of the power house. At this point they are joined and continued as one opening. The draft tubes were moulded in the concrete and steel forms were used to produce the desired surface. As a considerable portion of the concrete surrounding the draft tubes was placed during winter weather the steel forms afforded an excellent opportunity to build fires inside and keep the temperature above freezing. The superstructure consists of a brick building with two concrete floors. The entire structure rests on a foundation of sand and is supported on piles. No settlement cracks have been noticed after two years of operation.

Generating Units.—Each turbine unit consists of four 64 in. wheels on a single line of horizontal shafting. The turbines are designed to operate under a head varying from 22 to 34 ft., and under a maximum head each unit will develop 4,000 hp. The shafts are extended through the bulkhead and connected to 2,500 kw. generators. There will be eight generator units. Six of these are installed, two furnishing 60 cycle and the others 25 cycle current.

The turbine chambers are formed of reinforced concrete, with 3-ft. walls separating the various chambers. A 3-ft. wall also separates the generator room from the penstocks. Water is admitted to each turbine unit through three openings between concrete piers. Each opening is 10.5 ft. wide and is controlled by a double-leaf steel gate. The gates are operated from a gantry crane that may be moved the entire length of the power house.

A transmission line runs to Portage, 24 mi., where it connects with the existing 25 cycle line extending from the Southern Wisconsin Power Co.'s hydroelectric plant at Kilbourn, Wis., to Milwaukee. Another transmission line runs direct from Prairie du Sac to Madison, 28 mi., and two short lines serve half a dozen villages in the neighborhood.

XXII. INDUCTION GENERATOR STATION OF GREENFIELD (MASS.) ELECTRIC LIGHT AND POWER COMPANY ON GREEN RIVER.

An interesting installation on the Green River in Massachusetts consists of a 24 in. double runner horizontal water wheel belted to a 100 hp. three-phase 2300 volt squirrel cage induction motor driven above synchronous speed to operate as an induction generator. The water wheel is controlled by a governor which holds the load speed at about 15 per cent. above normal. If the load should be dropped for any reason the set will not run away. The motor is connected through an automatic switch and meter to a 2,300 volt distribution line. Ordinarily there is sufficient load on the line to absorb the output of the induction generator; however at light load the output is fed back into the main station bus. The attention given to the plant is mainly at times of changes in shifts at the main station three times a day when the operator stops on his way to work to read the meter and make any necessary adjustments.

XXIII. A 5,000 Kw. Development Near Defiance, Ohio.

The dam for the development in Fig. 57 is made up of 25 15-ft. bays, with a total length of 375 ft. Three gates, each 30 ft. wide, and the main generating room of the power house, 145 ft. long, are built across the bed of the stream and form part of the dam. At this point the river is 610 ft. wide, and under normal conditions the dam furnishes an effective head of 26 ft. There are in all, 11 gates—two for each generator and one for the exciter unit. The gate hoist is able to raise a single gate in about 15 minutes. The hoisting mechanism is driven by a 5 hp. motor taking energy from one of several outlets in the wall along the track. The gates are hoisted from a 10-ft. gate house running the full length of the generating station on the up-stream side. At the site of the power house and dam, as well as many miles up-stream, the river banks rise abruptly to an approximate height of 30 ft., affording an excellent natural basin for impounding water in the periods of maximum river flow.

Generating Units.—This generating station contains five 1,000 kva., 2,300 volt, 25 cycle, three-phase, star-connected, revolving-field alternators spaced in a single row down the middle of the plant at a distance of 23.5 ft. between centers. The vertical turbine wheels, which run at a speed of 94 r. p. m., measure 9 ft. in diameter, and each is equipped with 20 buckets. All wheels are of the single-runner type and the weight of the rotating element is carried by a huge bearing at the top of the machine. Three guide bearings spaced along the vertical shaft keep the rotating parts in alignment. Both the main bearings and the guide bearings are water-cooled. With the water level at the spillway crest a 22 ft. head is obtained at the wheels.

The turbine bearings are oiled from the floor of the station by an automatic pump which supplies oil at pressures varying from 200 lb. to 300 lb. per sq. in. A pressure relay in the oil system controls the automatic starter of the motor-driven oil pump. The turbine governors are all supplied with oil at 160-lb. pressure from a central oil pressure system. The two 25 cycle, 220 volt, 40-hp. motors driving this apparatus are automatically started and stopped by the pressure variations of the system. Two motor-driven pumps supply water at a pressure of 40 lb. to the transformers and generator bearings and for other general purposes.

Exciters.—The exciter equipment is divided into three units, one of which is a 125 kw., 125 volt, machine driven by a vertical water wheel of the same type as the larger units. This exciter is used only when the water supply is plentiful. The other two units are driven by 25 cycle, 2300 volt induction motors and are capable of producing 125 kw. and 75 kw. respectively. All of the exciters are wired so that they may be switched to a

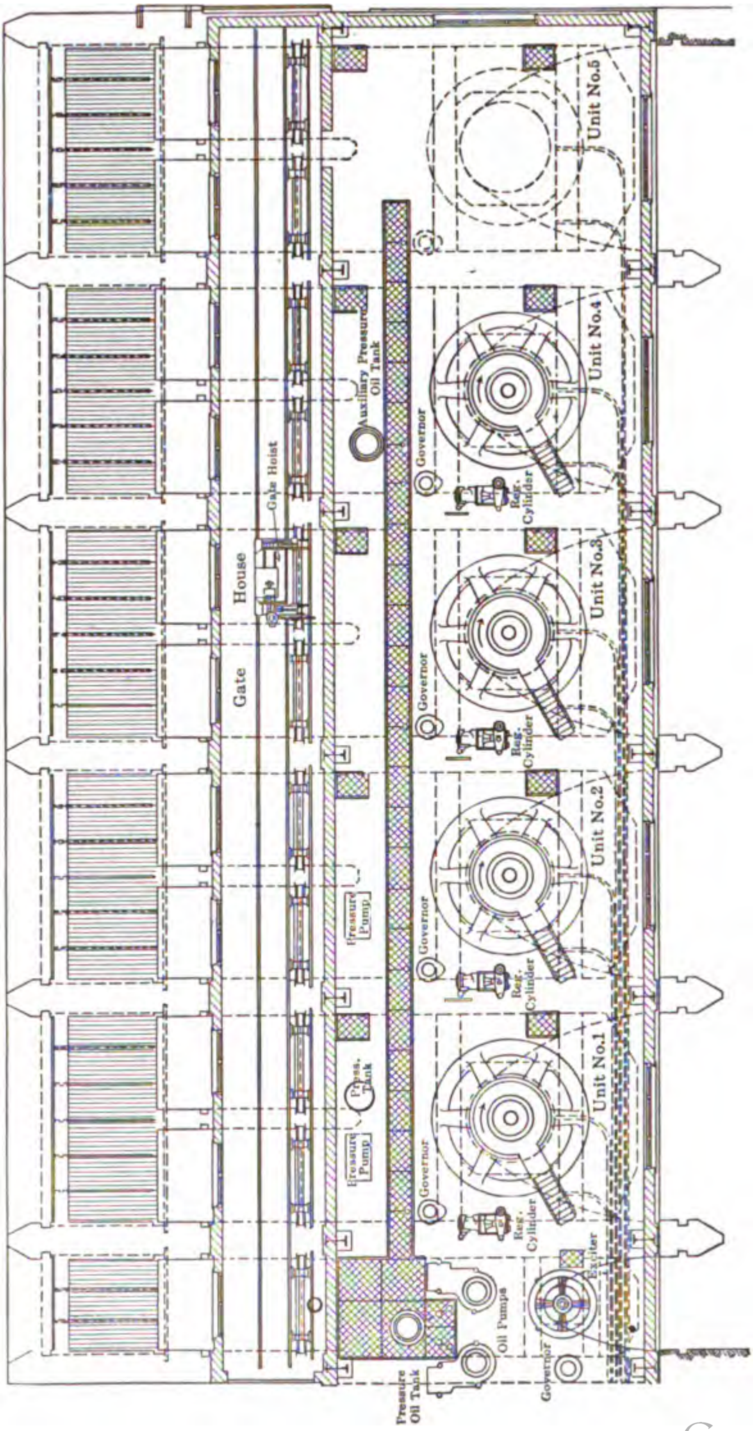


Fig. 57a.—Plan of 5,000 Kva. Station on Anglaize River near Defiance, Ohio

common bus from which energy is distributed to the field windings of the alternators. A 40-ton crane serves all portions of the generating room.

For stepping up the voltage as the energy leaves the station five three-phase, 1,000 kva., 2300/34,600 volt, 25 cycle, composite-type transformers have been installed. These water-cooled units have both their primary and secondary windings connected in delta. Each of the main groups of transformers feeding the transmission line is protected on the transmission-line side by aluminum-cell lightning arresters designed for use on circuits operating at 60,000 volts.

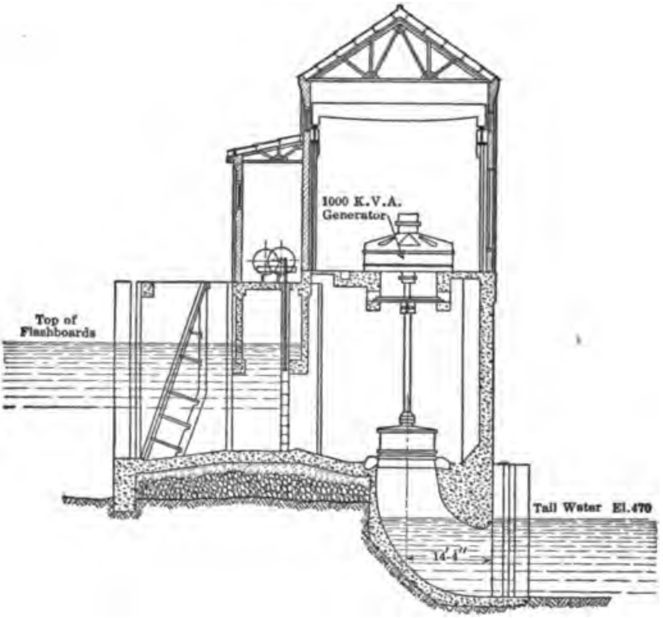


Fig. 57b.—Station on Anglaize River near Defiance, Ohio, Operated by Anglaize Power Company

This plant was completed in 1912. Its equipment consists of five Allis Chalmers 1000 kva. 2,300 volt, 25 cycle, three-phase Y connected generators driven by vertical turbine wheels at a speed of 94 r. p. m. The operating head is 22 ft. The transmission voltage is 34,600. The engineering work was in charge of R. R. Livingston, consulting engineer, New York City.—*Electrical World*, November 1, 1913.

XXIV. TALLULAH FALLS DEVELOPMENT OF GEORGIA RAILWAY AND POWER COMPANY IN NORTHERN GEORGIA.

The Tallulah Falls generating station shown in Fig. 58 is 192 ft. long by 48 ft. wide, and contains space for six main units spaced on 28 ft. centers. The lower chords of the roof trusses are 49 ft. above the generator-room floor. Massive concrete construction was used for the foundation, the walls being of concrete to an elevation 1.5 ft. above the main generator floor. The generating-room floor is constructed with heavy steel girder beams to distribute the load from the generator frames, and the concrete is monolithic with the side walls. The structural-steel framework of the building rests on solid concrete foundation walls. A plate girder runway is provided

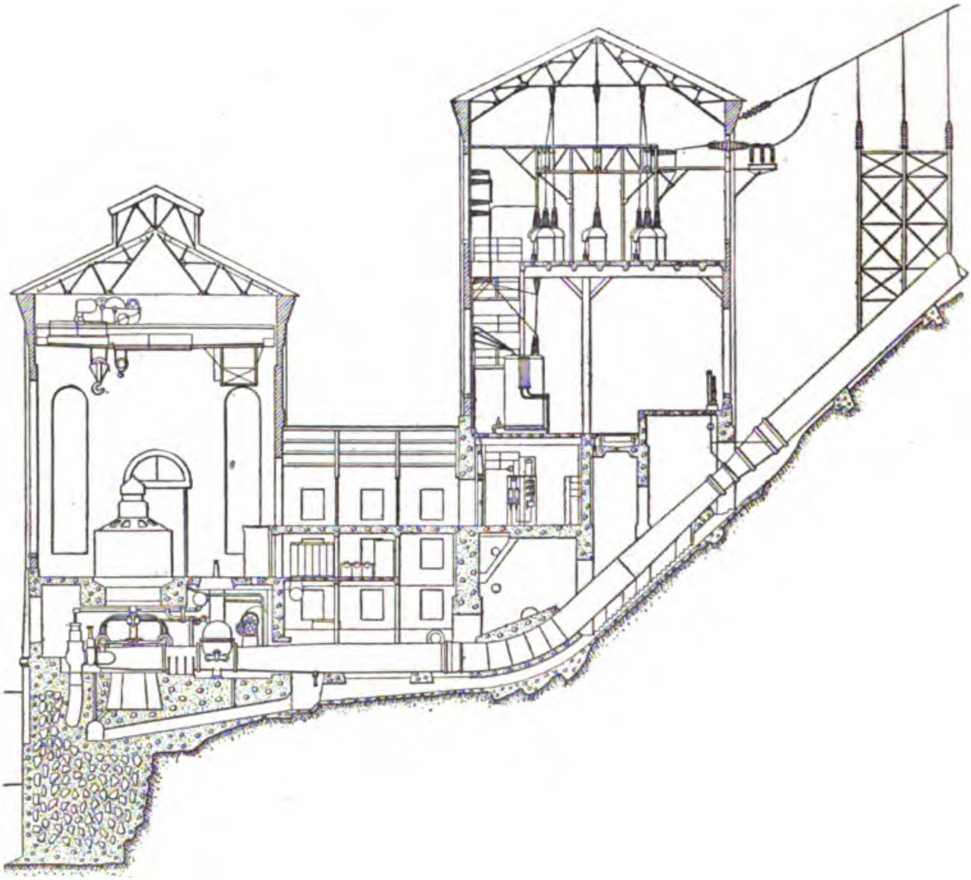


Fig. 58.—Tallulah Falls Station of the Georgia Railway and Power Company

The development of which this station is a part consists of a storage reservoir with a capacity of 1,400,000,000 cubic feet; a diversion dam six miles below on the Tallulah River, a special intake to a concrete lined tunnel 6,670 ft. long through solid rock to a structural steel reinforced forebay and surge tank. From this surge tank five steel penstocks, 1,200 ft. long, 5 ft. in diameter with a provision for six, lead to the power station containing five 12,000 kva. General Electric generators with provision for six, each driven by a 18,000 hp. vertical shaft S. Morgan Smith Francis type turbine operating under a head of 600 ft. at 514 r. p. m. From this station energy is transmitted over a double circuit steel tower transmission line at 110,000 volts to outdoor substations located in different parts of the State of Georgia. The storage at Tallulah Falls is 63,000,000 cubic ft., made available for the water wheels by the main or diversion dam at times of smallest stream flow. Based on lowest recorded stream flow, the minimum available power due to both the diversion dam and the Mathis storage dam is 90 million kw.-hr. per year. According to the average recorded stream flow for years 1900 to 1913 there is available 125 million kw.-hr. per year with the proposed power plant at Mathis dam raising this figure to about 140 million kw.-hr. on a 24 hr. operating basis. The Tallulah Falls development was designed by C. O. Lenz, consulting engineer, New York City, and the construction in charge of Charles A. Adsit, for the Northern Contracting Company. The plant was placed in operation late in 1913.—*Electrical World*, December 20, 1913, and January 8, 1916.

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for a 60-ton crane. The side walls of the generating station are constructed of red brick with marble pilaster caps and window sills. The roofing is of reinforced-concrete tile construction colored red to harmonize with the coloring of the side walls of the building.

Power Station.—The general construction of the transformer and switch house building is similar to that of the main generating station building, except that there is no monitor and the roof trusses are of a special design with a raised cord to provide space for the necessary buses without unnecessarily raising the walls of the building. A straight-flight steel stairway with landings connects all the floors. A traveling trolley hoist electrically operated is installed for raising materials to the upper floor. The transformers are placed on one side of a track which forms the runway for a transformer truck.

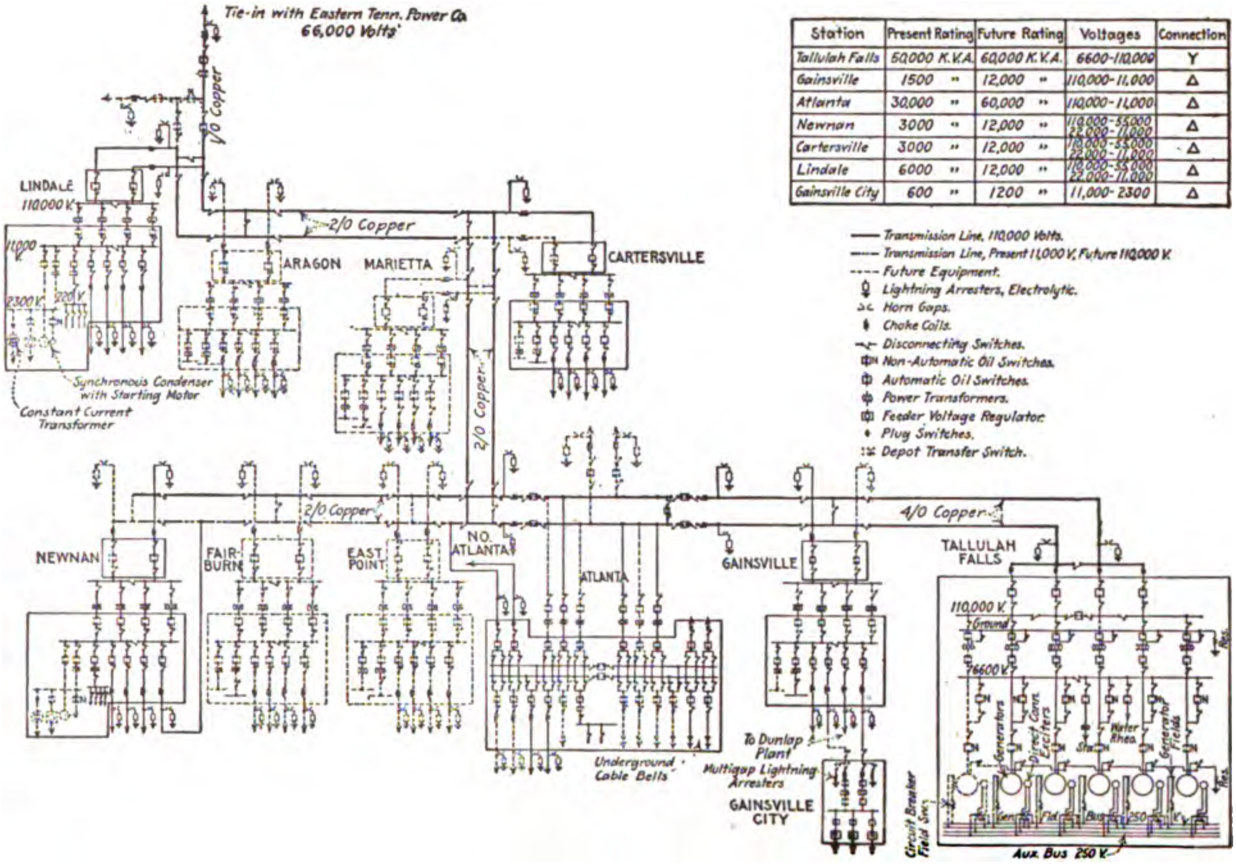
The first floor contains a 250 kw. Pelton water wheel, tapped off from the penstocks, which is used to run an auxiliary exciting generator, and also a small compressor plant to supply air for cleaning and other purposes. The transformer room is above the low voltage room, the elevation of the low voltage switch-room floor being the same as that of the gallery in the generating station. This room provides space for 18 transformers. The high voltage switch-room is located over the transformer room and contains all the high voltage switching gear of the station, as well as the high voltage buses from which the electrical energy is taken by the transmission lines. The transformer and switch house is 250 ft. long by 50 ft. wide, and is situated on the side hill of the gorge back of the generating station so that the front wall is 25 ft. to the rear of the back wall of the generating station.

Penstocks.—From the forebay the water is conducted to the turbines through 60 in. penstocks, there being six of these installed, one for each 18,000 hp. unit. The penstocks are of riveted steel varying in thickness from $\frac{3}{8}$ in. to $\frac{9}{16}$ in., and are from 1,200 ft. to 1,258 ft. in total length from the forebay to the power plant. The greater portion of the penstocks are on grades exceeding 70 per cent., the maximum grade being 150 per cent.

At the upper end of the penstocks remote-controlled motor-operated gate-valves, 60 in. in diameter, are provided. These valves are provided with limit switches and are operated from the generating station. At the lower end of the penstocks a heavy anchorage casting of cast-steel is solidly embedded in the concrete of the generating station and connected with the turbine casting on one side and with a hydraulically operated gate valve. Above the hydraulic gate valve and just outside the generating station building a Venturi meter with 35 in. throat is installed in each penstock. The penstocks are carried on concrete piers. At or near each change of grade a heavy concrete anchorage block is provided for each straight section over 100 ft. in length. (See Fig. 8, page 19.)

Water Wheels.—The water wheels in the Tallulah Falls station of the

Georgia Railway & Power Company were placed in service during the latter part of September, 1913. They were originally specified for a normal rating of 16,000 hp. at 580 ft. effective head when operating at 514 r. p. m. with



Station	Present Rating	Future Rating	Voltages	Connection
Tallulah Falls	50,000 K.V.A.	60,000 K.V.A.	6600-110,000	Y
Gainsville	1500 "	12,000 "	110,000-11,000	Δ
Atlanta	30,000 "	60,000 "	110,000-11,000	Δ
Newnan	3000 "	12,000 "	110,000-55,000 22,000-11,000	Δ
Cartersville	3000 "	12,000 "	110,000-55,000 22,000-11,000	Δ
Lindale	6000 "	12,000 "	110,000-55,000 22,000-11,000	Δ
Gainsville City	600 "	1200 "	11,000-2300	Δ

Fig. 59.—System Connections for Substations and Transmission Lines of Georgia Railway and Power Company

the generators connected to them rated at 10,000 kw. On account of the fact that the design of the generators exceeded contract specifications, it was found that they could carry 12,000 kw. continuously at 80 per cent. power-factor and a temperature rise not exceeding the specifications for 10,000 kw. (40 deg. C.). The water wheel ratings were therefore modified by the builders and increased to 18,000 hp. normal, to conform with the increase in generator rating. The units have carried 19,000 hp. during tests. Five units are installed with provision for a sixth, making the ultimate station capacity 108,000 hp. under normal operating conditions. These units have been in continuous service since being installed.

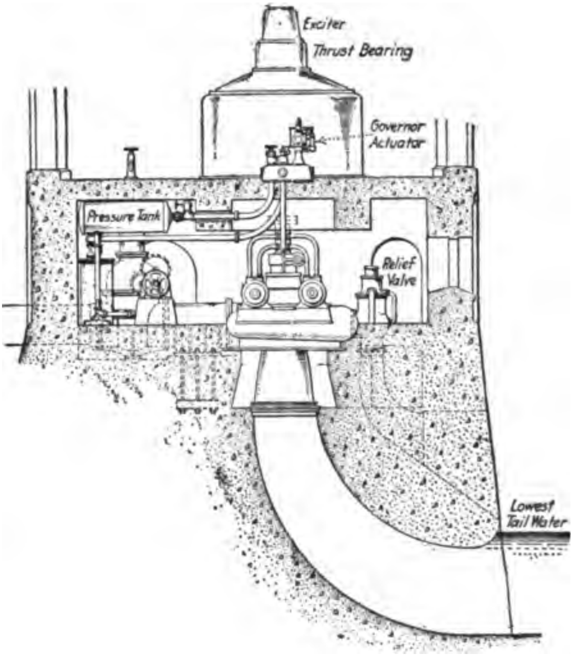


Fig. 60.—Section Showing Water Wheel Setting, Inlet Relief Valve and Draft Tube Connections at Tallulah Falls Station of Georgia Railway and Power Company

The water wheels are of the vertical shaft, commonly known as the Francis type, equipped with bronze runners and forged steel gates. The wheel shaft is of a special grade of forged steel, made in two sections, the lower 14 in. and the upper section 16 in. in diameter. The complete shaft weighs 20,000 lbs., and the complete turbine unit weighs 300,000 lbs. The spiral casing of each unit is made of special grade cast iron in one piece, with an inlet diameter of 45 in. connected to a hydraulically operated 45-in. gate valve for cutting off the water from the spiral case. A 20-in. nozzle tangentially opposite the 45-in. inlet is provided on the scroll case equipped with a 20-in. heavy gate valve and a 20-in. relief valve, the latter being under the control of the governor. The relief valve is designed to discharge 70 per cent. of the discharge of the turbine under operating head with sudden closing of the gates, and is connected to the scroll case of each water wheel on a center line with the penstock connection.

Draft Tubes.—The discharge from the wheels is through draft tubes, the upper section of which is of cast iron fitted with two large man doors directly opposite one another, and this section passes through a chamber under the turbine floor from which access can be had to the draft tube under the runner. The lower end of this section terminates in a cast-iron curbing which is built into the floor of this chamber, and the connection between the draft tube and the curbing is made by means of a bell and spigot joint. To the lower flange of this curbing is riveted a draft tube made of plate steel and built into the concrete from the floor of this chamber to the point where it discharges into the tailrace. The center of the wheel is set 22 ft. above the level of water in this tailrace.

While the water wheels were designed to operate under and tests were computed for a net effective head of 580 ft., the actual head under which the plant operates is 606 ft., owing to the natural fall of the Tallulah River and a 110-ft. dam. This is at present the highest head under which turbine wheels are being operated in the United States.

Acceptance Tests.—By contract agreement between the S. Morgan Smith Company, the builder of the wheels, and the Georgia Railway & Power Company the units were to be tested before acceptance to determine the amount of bonus or forfeiture to be considered in connection with the contract price. This bonus or forfeiture by agreement was based on the difference between 83 per cent. and the efficiency shown by test when the unit was developing 0.8 of its maximum power (about 19,000 hp.) at 514 r. p. m. under 580-ft. head.

Efficiency of Water Wheels.—Although five units were installed and in operation, it was decided to test three units, and for convenience of operation Nos. 2, 3 and 4 were selected. During the test of each of these machines the other four were shut down and their hydraulically operated gate valves closed. The efficiency of unit No. 2 at 80 per cent. of its maximum output was 88.3 per cent. The highest efficiency for this unit was 89.3 per cent. at 0.76 gate opening and 16,750 hp. The efficiency of unit No. 3 at 80 per cent. of its maximum output was 89.9 per cent. The highest efficiency for this unit was 90.4 per cent. at about 0.75 gate opening and 16,875 hp. The efficiency of unit No. 4 at 80 per cent. of its maximum output was 88.7 per cent. The highest efficiency for this unit was 89.50 per cent. at approximately 0.76 gate opening and 16,900 hp.

The load on the generators was obtained by means of two three-phase, star-connected, 63,500 volt water rheostats connected on the primary side of the station step-up transformers, giving approximately equal loads on the three phases at approximately unity power-factor. The output of the generators was measured by means of a standard indicating wattmeter connected to instrument transformers which were connected to the generator terminals. The current and two potential transformers were connected in open delta on the secondaries and connected to the coils of the indicating wattmeter to measure the total output. In addition to the indicating wattmeter, a standard watt-hour meter, an indicating ammeter and voltmeter were used. The ammeter and voltmeter were transferred to all the three phases for three-phase readings.

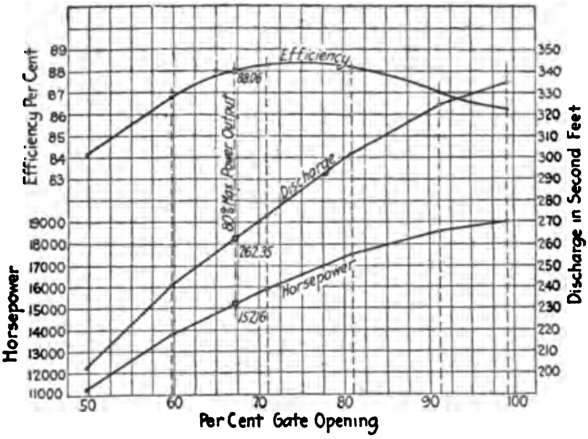


Fig. 61.—Curves Showing Average Power and Efficiency on which Bonus for Water Wheels in Tallulah Falls Station was Accepted and Paid

Calculating Efficiencies of Generators and Exciters.—The efficiencies of the exciters for the various outputs were taken from a large-sized efficiency curve, which had been plotted from data obtained from the shop tests of the machine builders. The exciter outputs were divided by the efficiencies taken from the curve in order to obtain the exciter input. Efficiency curves for the generators were plotted from shop-test data of each machine, and the efficiencies obtained from these curves for the various outputs were used to obtain the generator input. The efficiencies obtained in this way included excitation.

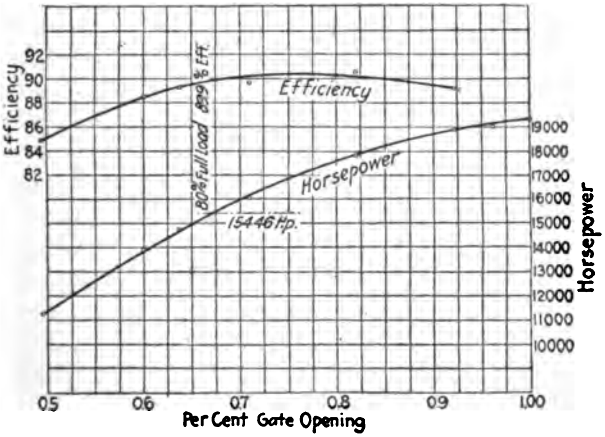


Fig. 62.—Power and Efficiency for Unit No. 3 in Tallulah Falls Station which Showed the Best Performance

The power delivered to the water wheel shaft was derived by taking the generator output and dividing it by the shop efficiency of the generator, which included the excitation among other losses. The exciter output was then divided by its shop efficiency. These two results were then added together, and from this sum a deduction for excitation was made. The final result was the net power delivered to the water wheel shaft.

Generators.—The generators are of the vertical type rated at 12,000 kw., 514 r. p. m., 6,600 volts, 60 cycles, three-phase, with 100 kw., 250 volt exciters mounted on the dome of each. Each exciter is capable of exciting two generators at its full load. These generators complete have a flywheel (WR^2) effect of 1,250,000 ft.-lb. The switchboards overlook the main operating room of the switch-control house which joins the generator building to the switch house. A benchboard contains all the control switches, mimic buses, signal lamps, etc., and directly in the rear are the vertical instrument panels containing indicating and other instruments.

Three 3,333 kva., single-phase transformers per generator group step up the voltage from 6,600 volts to 63,500 volts, giving 110,000 volts to the line potential when star-connected. The neutral of these transformers is connected through a neutral resistor at the end of the switch house. From the high voltage terminals of the transformers the energy is carried through high voltage oil-switches, buses, etc., to the outgoing transmission lines.

XXV. DEVELOPMENT OF SALMON RIVER POWER COMPANY

The development shown in Fig. 63 is of special interest because of its several novel hydraulic features. The main dam creates a reservoir which has a capacity of 2,600,000,000 cu. ft. with the dam-crest at 935 ft. above sea level. At the average rate of flow of the stream, about 20 days are required to fill it. With the crest at this elevation the average net head produced at the generating station less than 2 miles away is 245 ft.

Pipe Line.—The conduit connecting the dam and the generating station consists of five sections, a 600 ft. reinforced-concrete-lined tunnel drilled through rock, a 7,825 ft. length of wood-stave pipe, a 1,200 ft. length of steel pipe, a steel surge tank and four short penstocks. The tunnel is lined with concrete not less than a foot in thickness with circumferential reinforcing rods closely spaced, and has an inside diameter of 12 ft. The wood-stave pipe continues at the same diameter for 3,450 ft., the diameter being reduced to 11 ft. for 4,375 ft. more. The staves are of kiln-dried fir cut out not less than 3⅝ in. thick for the 12 ft. pipe and 4 in. for the other. They are joined end to end by means of galvanized-iron keys and are held circumferentially with bands of ⅞ in. and 1 in. steel rods. Each band is in three sections, all united by cast-iron clamps. In soft ground the pipe was supported on timber cradles, but otherwise it was laid directly on the surface. It was coated on the inside with carbolineum and afterwards backfilled to about one-half its height. Relief valves are inserted at intervals to prevent undue pressure when emptying the pipe, and to serve as air outlets when filling. Drains are placed at all low points of the line.

Wood pipe was selected for that part of the conduit in which the pressure was not too great because where it was installed the winters are very severe and it is cheaper than steel pipe when the latter is properly protected from freezing. Fir was used because it is an excellent wood for pipe not subjected to alternate wetting and drying in that it remains tight, does not rot and its cost is quite reasonable. The steel-pipe section is 1,200 ft. in length and 11½ ft. in diameter. It is connected to the wood pipe through a slip expansion joint packed with oakum and lead wool. Special attention was given to the material in this pipe, which was specified as open-hearth steel containing not over 0.05 per cent. sulphur and between 0.3 and 0.6 per cent. manganese. The phosphorus was limited to 0.06 per cent. if the steel was made by the acid process and 0.04 per cent. if by the basic process. The thickness of the pipe is ⅝ in. throughout. The steel pipe is mounted on concrete saddles 20 in. thick and spaced about 14 ft. apart. It is laid in a shallow well-drained trench and a 6 in. sewer tile is molded in the bottom of each saddle to facilitate drainage. The pipe is housed over with a substantial structure of framing and boarding continued down to the ground level.

On the crest of the ridge just behind the generating station is a distributer consisting of a 12 ft. steel pipe 210 ft. in length and joined at one end to the pipe line in a huge concrete anchor block. The other end is closed by a bulkhead. The elevation of the bottom of the distributer is 775 ft., or 160 ft. below the crest of the dam. From the center of the distributer a 12 ft. riser branches off to a surge tank. This enormous T-connection required reinforcing from side to side. This was provided by a 9 in. bolt, 25 ft. long, with bearing washers for the nuts 4 ft.

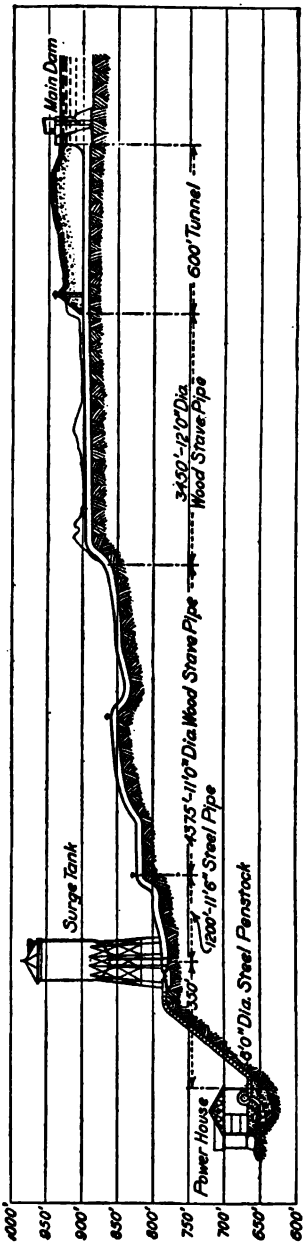


Fig. 63.—Dam, Pipe Line, Surge Tank and Power Station of Salmon River Power Company's Development

This station operates in parallel with Niagara, Lockport and Ontario Company's system. The station contains four Francis horizontal single spiral double discharge turbines that operate under a head of 245 ft. and are rated at 10,000 hp. each. The generators are rated at 5,600 kva., 6,600 volts, 25 cycle, three-phase at 375 r. p. m. and will carry 20 per cent. over load. The transmission voltage is 60,000. The operating head of 245 ft. is secured between the dam and power station two miles away.—*Electrical World*, June 13, 1914.

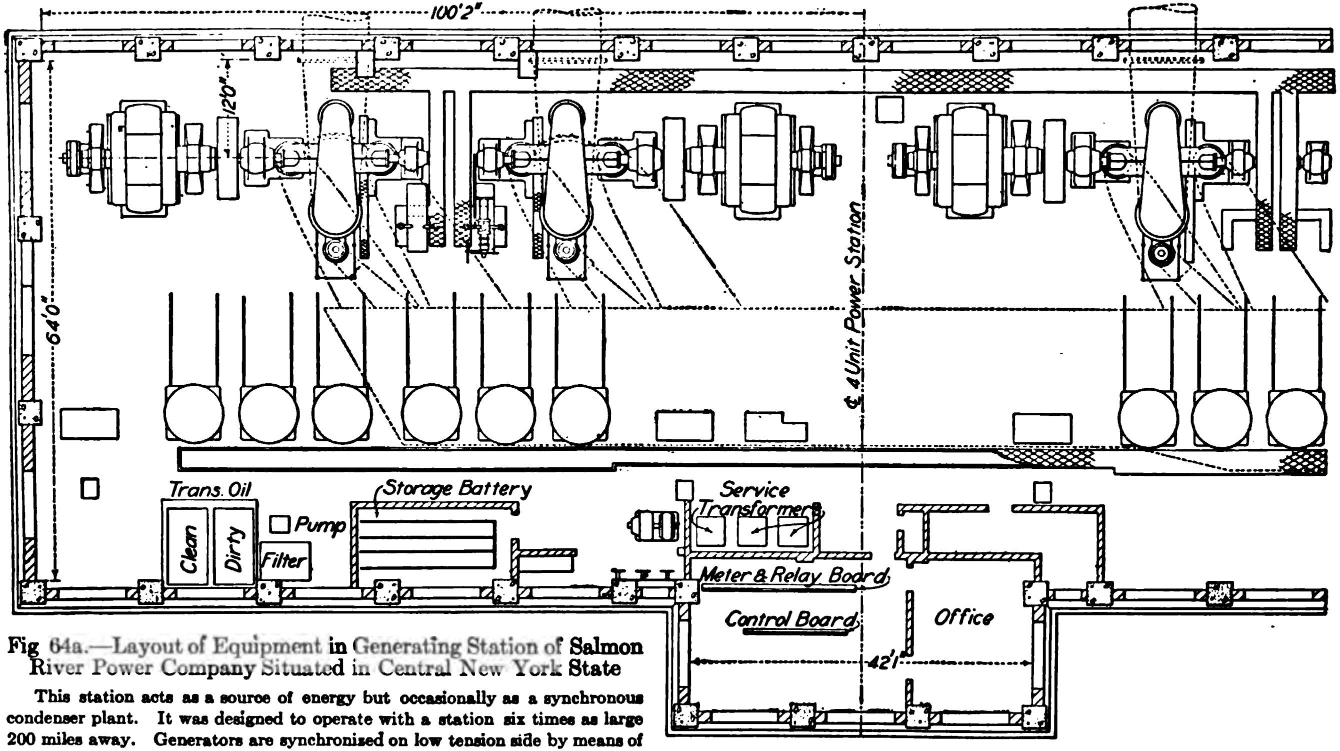


Fig 64a.—Layout of Equipment in Generating Station of Salmon River Power Company Situated in Central New York State

This station acts as a source of energy but occasionally as a synchronous condenser plant. It was designed to operate with a station six times as large 200 miles away. Generators are synchronized on low tension side by means of three shunt transformers. Two of these are connected to the circuits on one side of the oil circuit breaker and used for the instruments and relays. On the generator side of the circuit breaker a special shunt transformer is used for voltmeter, regulator and synchroniser (see Fig. 65.) The system was designed by Barclay, Parsons and Klopp as consulting engineers and in charge of hydraulic construction. V. G. Converse, chief engineer Salmon River Power Company, in charge of construction.

in diameter. The surge tank riser joins the distributer with easy curves, but a novel and cheaper connection is made to the penstock intakes, 8 ft. in diameter. This is a simple flanged and riveted joint, which would, without some modification, produce eddies and loss of head. To prevent such, wooden fillers suitably rounded off are secured around the mouths of the intakes inside the distributer. This distributer is a steel pipe, ⅝ in. thick, inclosed in concrete.

Surge Tank.—The surge tank is one of the largest of its type yet constructed. It consists of a cylindrical shell, 50 ft. in diameter and 80 ft. high, surmounting a hemispherical bottom which adds 25 ft. to its height.

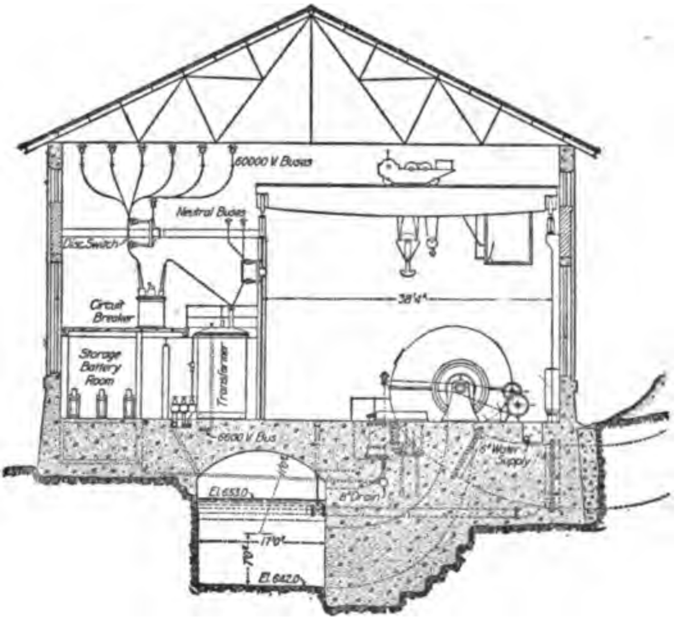


Fig. 64b.—Section Through Station of Salmon River Power Company

Its capacity is, therefore, 1,400,000 gals. The tank is supported on ten columns of heavy concrete footings and with the riser are housed in with a framed wooden structure providing a surrounding space which can be heated when necessary from a small house below. The top of the roof of this structure is 205 ft. above the ground, and the top of the tank is high enough above the crest of the dam so that if the flow of the water in the pipe line were suddenly interrupted its energy would be absorbed by the rise in level in the tank without overflow.

There is an important feature of this surge tank riser. With a 12 ft. riser opening into the bottom of the tank there would not be friction enough to absorb the energy of a surge, which would therefore tend to set up oscillations. To provide for the damping of such oscillations, a smaller pipe is mounted inside the tank, connected directly to the riser below and terminating in the funnel near the top. The rest of the mouth of the riser at the bottom of the tank is covered by a ring in which small ports are provided. In action, therefore, a surge produces a rise in the small pipe and some flow through the ports. The head in the small pipe then forces the surplus water through the ports and equalizes the pressure gradually.

Penstocks.—The four 8 ft. penstocks are connected to the intakes through valves of a type which represent a comparatively new development in hydraulic practice. These penstocks are anchored above and below in heavy concrete blocks, and laid in trenches and entirely back-filled. The steel plates vary in thickness from ½ in. on the upper horizontal portion of the penstocks to ⅞ in. at the lower end where they enter the generating station.

Turbines.—The four turbines are of the Francis horizontal single-spiral double-discharge type of 10,000 hp. rating each. They are provided with outside, balanced wicket gates operated by governors. These turbines are provided with heavy flywheels to assist in governing and to facilitate the operation of the electrical equipment of the plant in parallel. They are also provided with relief valves operated by the governors, so that the sudden checking of over-speed cannot result in an excessive rise in pressure. The discharge of the turbines is conducted to the tailrace through short concrete draft-tubes, entering at an obtuse angle to prevent eddies. In fact, on its entire journey from the reservoir to tailrace the water is led with as few turns as possible and around easy curves. The tailrace is directly under the generating station, which is built over the bed of a branch of the river that previously carried water at times of flood.

Power House.—The generating station building is a single structure consisting of reinforced-concrete pilasters connected with heavy concrete beams. The panels are filled with red brick outside and sand-lime brick inside. The roof, supported on steel trusses, is 3 in. thick, of gypsum composition reinforced with steel cables and rods. The roof is covered with an asphalt coating overlaid with several layers of asbestos felt. One purpose in the use of this particular type of roof was to secure a fireproof base on which tile could be nailed in case it was later found desirable to add a tile roof. The gypsum roof is very easy to place and is very light. The building is rectangular with a projecting feeder bay. The interior is open to the roof and, with the exception of a gallery about 12 ft. above the main floor on the feeder-bay side, forms one great room. It is served by a 40 ton electric crane with main and auxiliary hoist all driven by direct current motors. The crane has a 38 ft. span and the runway covers the entire length of the building. The intake pipes, the draft tubes and the discharge tunnel are all directly under the building, embedded in concrete.

Each of the four electrical generating units consists of a 375 r. p. m., 6,600 volt, 25 cycle, three-phase generator with exciter mounted on an extension of the shaft. Three 2,200 kva., single-phase, 25 cycle transformers are installed with a normal ratio of 6,600 volts to 34,650 volts. The high voltage side is connected in star to give a line voltage of 60,000 volts.

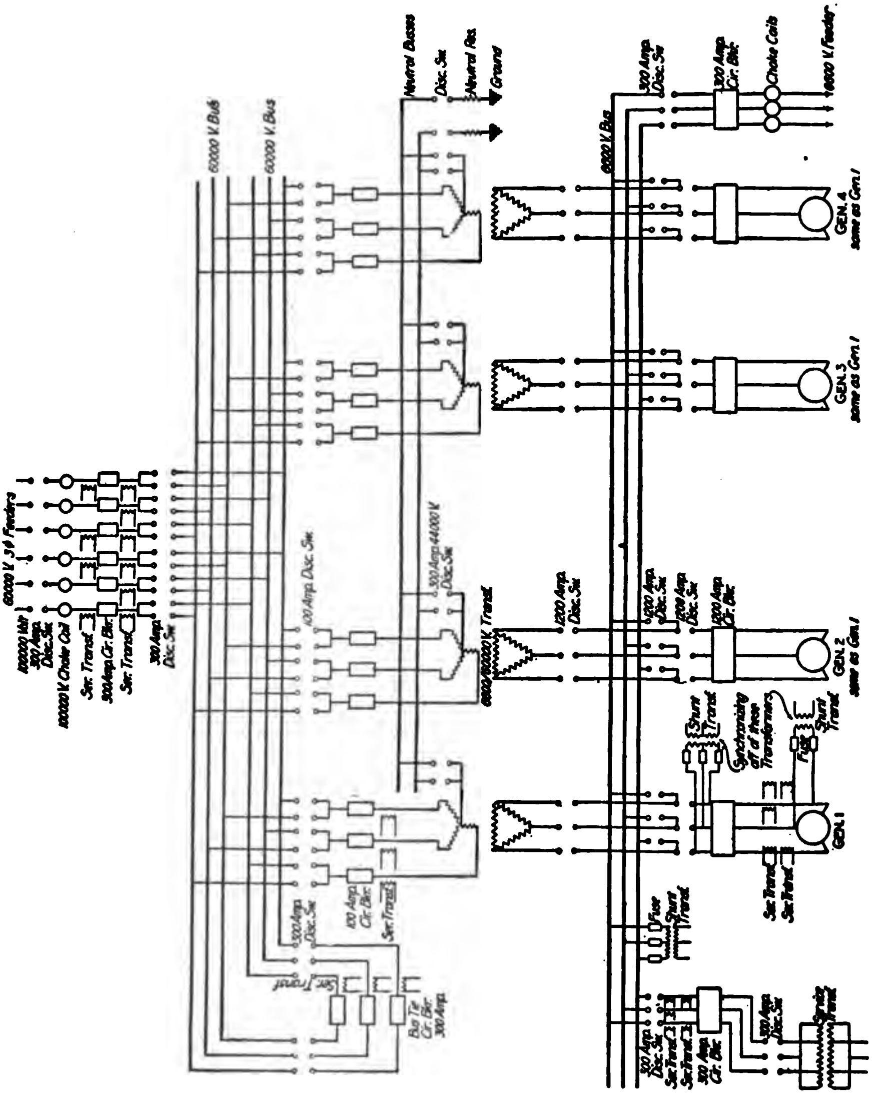


Fig. 65.—Circuits of Salmon River Power Company's Station Tied in with Niagara Falls Plant of Ontario Power Company

XXVI. BIG CREEK DEVELOPMENT PACIFIC LIGHT AND POWER COMPANY NEAR FRESNO, CAL.

The initial step in the development shown in Fig. 66 comprised the installation of two power houses, four concrete dams, two tunnels, two 240 mile transmission lines operating at 150,000 volts, substation and switch-station facilities, and a 56 mile standard gauge railroad. The development has an ultimate rating of 350,000 hp. The watershed is at an elevation of 7,000 ft. at all points. The annual rainfall is over 80 in. and the run-off about 50 in. It has a fall of about 4,000 ft. in 6 miles from a natural basin in the mountains. This drop is utilized in two points, the effective heads on the wheels being 1,900 ft. for the first development and 1,870 ft. for the second. The average daily flow is about 300 cu. ft. per second. In the natural basin a reservoir with an initial capacity of about 53,000 acre ft. has been formed by the construction of three dams built to an elevation of 6,915 ft. By raising the dams to an elevation of 6,965 ft. the capacity of the reservoir will be increased to about 120,000 acre ft. The utilization of this increased storage capacity with the natural flow of the stream will require the ultimate installation of at least four 20,000 hp. units in each plant. Two of these were installed in the initial development. The completed reservoir is 6 miles long, 1.5 miles wide and about 150 ft. deep. On account of the high heads developed it is estimated that this storage reservoir will carry 120,000 kw. at 50 per cent. load-factor for 240 days.

Pipe Line.—From the main dam water is conveyed through a 144 in. tunnel 3880 ft. long which terminates in a 108 in. Y with two 84 in. outlets. One of these is blanked for future service. The other is connected with an 84 in. flow pipe. At the top of the slope 1,942 ft. above the first generating station this 84 in. flow pipe opens into four 44 in. outlets. Two of these are connected with a penstock leading to the generating units, the others being blanked.

Four of the main units aggregating 80,000 hp. in the first station receive water from the 84 in. pipe line. This pipe is laid on a grade of 7.5 ft. per 1,000 ft. and is 6,480 ft. long from the tunnel outlet to the top of the cañon in which the generating station is situated. The pipe line is carried on concrete saddles placed 35 ft. apart, and the elbows are anchored by reinforced-concrete blocks. An earth covering of 12 in. minimum is placed throughout the line. Manholes are provided at 2,000 ft. intervals. The 84 in. pipe varies in thickness from 3/8 in. to 1/2 in., the longitudinal seams of the thinner plate being part double-riveted, while those of the thicker pipe are double-riveted.

At the top of each penstock is a 42 in. gate valve equipped for hand and motor operation with remote control from the power house. Just below the gate valves are two 24 in. standpipes, one in each line. These standpipes extend up the mountain side a distance of 425 ft. and terminate in two vertical surge tanks 3 ft. in diameter and 35 ft. high. The tanks ear anchored into concrete foundations, 10 ft. deep, 7.5 ft. wide at the top and

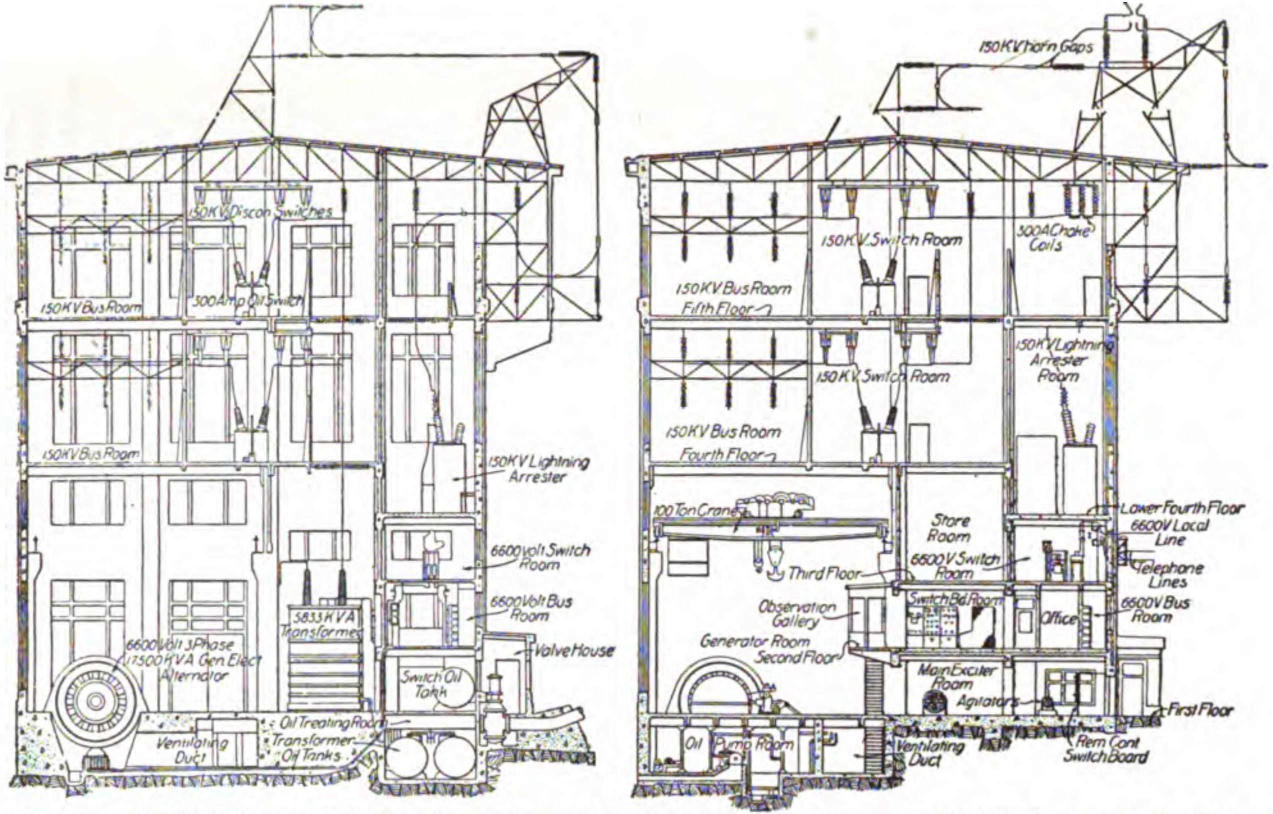


Fig. 66.—Big Creek Station of Pacific Light and Power Company Furnishing Energy to 150,000 Volt Transmission Line

When this station was placed in operation November 8, 1913, it was considered one of the greatest existing hydraulic and transmission undertakings. It supplies energy to a 240 mile, 150,000 volt transmission line which leads into the city of Los Angeles. This is both the highest voltage and longest line in operation and transmits about 160,000 hp. The station is located in Sierras National Forest, 70 miles east of Fresno, Cal. It was built under government permit, the largest granted, and allowed the construction of four power stations rates at 350,000 hp. two reservoirs and 25 miles of concrete, lined tunnels during 12 years. The initial development consisted of two stations, four concrete dams, two tunnels and a 240 mile transmission line. Station No. 1 contains four and No. 2 three, 17,500 kva. generators each direct connected to two impulse wheels of 10,000 hp. each. The operating head of station No. 1 is 1,900 ft. and for No. 2 1,780 ft.—*Electrical World*, January 3, 1914.

about 11 ft. wide at the bottom, by four cast-iron brackets held in place by foundation bolts 5 ft. long. The tanks are cross-connected by steel latticework near the top. The two penstocks run parallel at a distance of about 7 ft. to a point 800 ft. above the generating station, where each divides into two 26 ft. pipes, each similar pipe serving one runner of a water wheel unit. The penstocks are built in 30 ft. sections of lap-welded steel pipes varying in diameter from 42 in. at the top of the slope to 24 in. at the wheel inlets, the thickness ranging from $3/8$ in. to $1\frac{3}{16}$ in. The circular joints are riveted for pressures up to 1,460 ft., but for greater pressures are flanged and bolted.

Generating Units.—Each main unit consists of a 17,500 kva. generator directly connected to two impulse wheels of 10,000 hp. rating each, the wheels being overhung outside the bearings carrying the shaft. Apart from operating under one of the highest heads thus far developed, these wheels are the largest of their type ever made. They are 94 in. in diameter on the impulse circle and each contains 19 cast-steel buckets held in position on a nickel-steel wheel disk by three pressure-fitted bolts. The water for turning the wheel disks is directed upon the buckets by means of a stationary nozzle with a governor-controlled needle valve. The weight of the impulse wheel disk, the reacting force from the jet striking on the buckets with a velocity of 300 ft. per second, and the weight of the generator rotor are all carried on two 20 in. by 64 in. ring-oiled, water-cooled, self-aligning, babbitted bearings.

The main shafts are of hollow, forged nickel steel, 20 in. in diameter at the rotor, their over-all length being about 29 ft. The normal speed of each unit is 375 r. p. m.

Turbine Governors.—Regulation of each unit is obtained by two oil-pressure governors, each of which independently controls the movement of one needle valve. The shaft speed may also be controlled by manipulating the governors by hand, and the needle valves are also connected with a remote electric speed control operated from the power-house switchboard. The governor arrangement permits operating either wheel of the unit without the other at the maximum efficiency, so that frictional loads can be handled with economy. Each of the governors operates a pressure regulator which automatically by-passes the water at times when the needle is closed with an automatic adjustment providing for slow closing in order to prevent excessive rises in pipe-line pressure. The pressure regulator is connected to the inlet pipe back of the nozzle, and when adjusted to act as a water-saving device it will open for a given pressure rise, closing automatically only when the pipe line pressure returns to normal. The regulator has the same discharge capacity as the nozzle, the water issuing from it having its velocity reduced by an energy absorber. It then flows into the tailrace below the main wheels. The tailrace is lined with steel to take care of the erosion which otherwise would result from the discharging water.

Each governor is provided with a load-limiting device so that each wheel cannot furnish more than a predetermined amount of power. This device allows the governor to close the gates when the speed goes above normal and when the demand upon the wheel is less than that of the maximum for which the governors are blocked. A safety device is provided to close the needle valve in case of breakage of belt driving the governor fly-balls. The valves for controlling the water supply to each nozzle are hydraulically operated and are of special design to meet the high head involved. Their operation is safeguarded by providing a hand-operating pump to supply water pressure at times when a pipe line may be empty.

Power Station.—All the generating and switching equipment is housed in a reinforced-concrete and structural-steel building measuring 171 ft. long by 84 ft. wide by 103 ft. high. On the first floor are the generating units, the exciters, step-up transformers and separate compartments for station service transformers, rheostats, a storage battery for switch operation and oil-tank installation. The building is of sufficient size to house three generating units and their auxiliary equipment. The pipe lines pass from the valve house under the operating-room floor to the wheels, and the steel-lined tailraces are located immediately under each, opening directly into the river. The main generating room is 168 ft. long by 43 ft. wide and is served from end to end by a 100 ton electric traveling crane. The main switchboard, which is of the benchboard type, is located on a gallery in the center of the operating room, immediately above the exciter bay, and by remote control it governs the generators, transformers, switch operation and auxiliary control of governors and exciter motors. Station No. 2 which takes water from No. 1 has the same rating and same type of equipment as No. 1 but contains one less unit on account of the greater amount of water required per hp. of output.

Exciters.—At the present time only two exciters are installed, both being designed for ultimate combined motor and water wheel drive. The wheel design provides for a single-runner 47 in. in diameter with 24 buckets inclosed in a steel-plate housing, the generator being mounted on a horizontal shaft with a common bed-plate. The maximum jet diameter is $1\frac{5}{16}$ in. and its speed 300 ft. per second. The exciter wheel nozzles are stationary, with hand-adjusted needle valves. Speed regulation can be obtained by either hand manipulation or automatic governors, and when the load decreases the jet is deflected from the buckets by a steel hood operated by the speed-controlling devices. The water for the exciter wheels is supplied by an 8 in. header pipe cross-connecting the four pressure lines, each wheel nozzle being served through a 6 in. branch. The valves are designed for a pressure of 1,000 lb. per sq. in., all having been tested to 1,500 lb.

Two synchronous condensers rated at 1500 kva. are used to maintain a voltage of 150,000 at both ends of the transmission line.

XXVII.—HYDROELECTRIC DEVELOPMENTS OF NEVADA-CALIFORNIA POWER COMPANY AND SOUTHERN SIERRAS POWER COMPANY ON BISHOP CREEK, INYO COUNTY, CAL.

The hydroelectric installation of the Southern Sierras Power Company had its beginning about ten years ago in furnishing energy to the Nevada mining district around Goldfield, Cal. As need for electric energy in California became greater and the possibilities of the Bishop Creek location were more fully appreciated, a plan for extension was formulated and the long line connecting Bishop Creek with the San Bernardino country was built and put into service. This line stretches over nearly 240 miles practically straightaway and is joined at each end to another transmission system, the northern one running northeast into Nevada, the southern one down to and across the Mexican line, making a total stretch from the power station of about 400 miles. The whole group of generating stations along the Bishop Creek watershed on the eastern slope of the Sierra Nevadas cover a distance of about 15 miles, with three capacious reservoir sites. They comprise in all seven stations, of which five are now in operation, forming a remarkable example of the complete utilization of a stream. The storage reservoirs are natural lakes ground out by glacial action.

The original station, operated under 1,100 ft. head, contains two 750 kw. and three 1,500 kw. generators driven by Pelton wheels. This plant was the first installed (1905) and since then four others have been added, and two more will be installed later having a combined rating of 32,250 kw. The first plant had 118 miles of transmission line to Goldfield and Tonopah, operating at 55,000 volts, while the longer line southward is designed for 140,000 volts.

Perhaps the most striking engineering feat performed was tapping the south lake reservoir from 600 ft. below the site of the dam, driving a tunnel into the solid granite, coming up to the lake, and breaking through the lake bottom to convert the tunnel into a pressure pipe. The end of the tunnel being 65 ft. under water, the task of cutting through involved some rather unusual work. It was actually accomplished by excavating very cautiously within about 20 ft. of the lake bottom and then cutting short laterals to provide a powder chamber for blowing up the bottom and admitting the water. The tunnel was tamped for 30 ft. with muck back of the powder, and when the 5,200 lb. charge was fired the end of the tunnel was blown out into the lake.

The transmission system of the Southern Sierras Power Company as a whole involves the longest transmission distances yet regularly attempted, although the main straightaway transmission is scarcely as long as that of the Big Creek line of the Pacific Light and Power Company, which has often been referred to as the longest high voltage line in the world. However, the most distant customers of the Southern Sierras line are actually across the Mexican border, 400 miles from the generating stations, although toward the southern portion of the system there are numerous ramifications covering a large part of the southern Californian territory. Perhaps the most interesting feature of the whole work is the comparative simplicity of the methods by which energy is transmitted and service is maintained. The center of control of the system is near Bishop, Cal., below the mouth of the

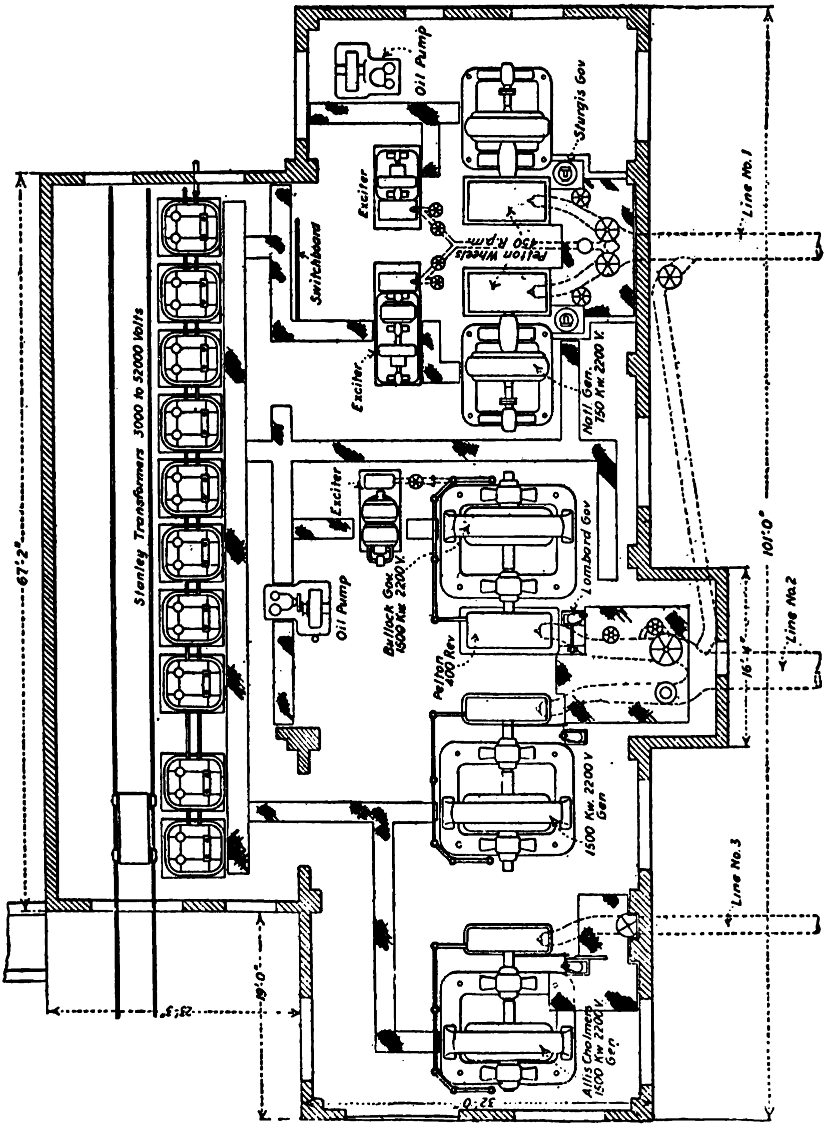


Fig. 67.—Station No. 4 of Southern Sierras Power Company

This is the original station of the system and operates under a head of 1100 ft.

cañon which contains the group of generating plants. This nerve center of the entire enterprise is free from elaborate buildings and intricate construction. The switching apparatus is of the typical outdoor type which characterizes all the later work of the Southern Sierras Power Company, although the transmitting system is designed for 140,000 volts. The station buses and the disconnecting switches through which the outgoing and incoming lines are connected to them are mounted on a framework of galvanized steel, and the double long-distance line which carries energy to San Bernardino and thus distributes it to the Mexican border is tied into the bus system with pneumatically operated air-break switches of the simplest possible construction. Even the instrument transformers are installed in the framework of the buses, and the leads are carried to the instrument room in which are also installed the pneumatic controlling devices for the synchronizing and other switches. The whole control system is noteworthy for its avoidance of the customary complications and the elimination of the enormous switchboard structures.

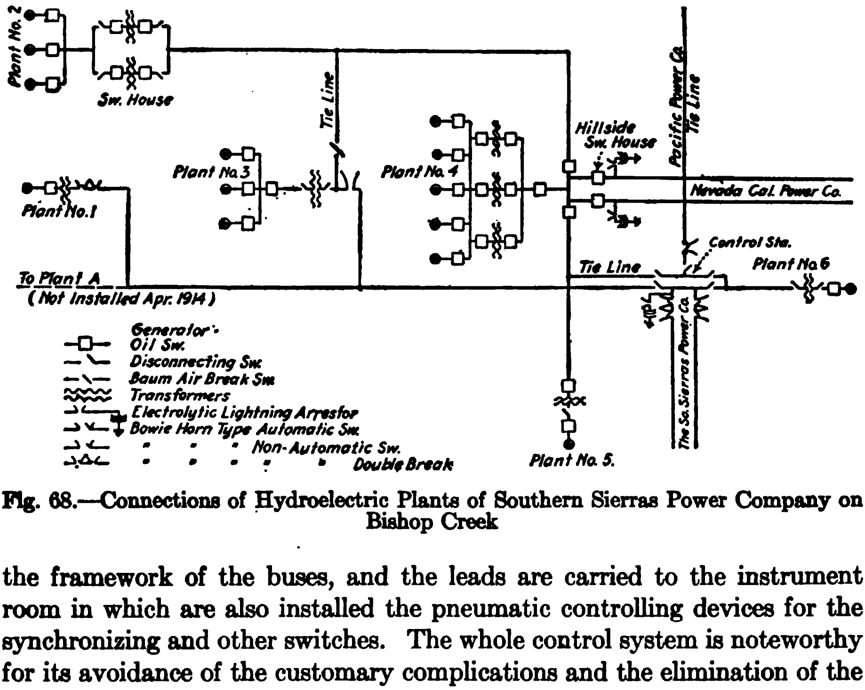


Fig. 68.—Connections of Hydroelectric Plants of Southern Sierras Power Company on Bishop Creek

XXVIII. DEVELOPMENT USING IMPULSE WHEELS IN SILT-LADEN WATER OF SALT RIVER PROJECT IN ARIZONA

The section shown in Fig. 69 is through the Cross Cut station of the Salt River Project near Phoenix, Arizona. The station has a rating of 5,250 kva. Special impulse water wheels were used on account of the fact that the water held a considerable quantity of silt in suspension and deposited a troublesome precipitate on iron and steel. These wheels are of a Pelton-Doble tangential design furnished by the Pelton Water Wheel

Company of San Francisco, each rated at 1000 hp. The unit consists of a vertical shaft with six nozzles set equidistant about the periphery of the runner. By changing the number of nozzles in use a practically straight line efficiency curve is obtained regardless of the amount of water passing through the power house. Small load variations are taken care of by deflectors, one for each nozzle. These are interconnected and controlled by a single governor for each unit. The station provides for six units each direct connected to a 875 kva., 25 cycle, 11,000 volt Westinghouse generator,

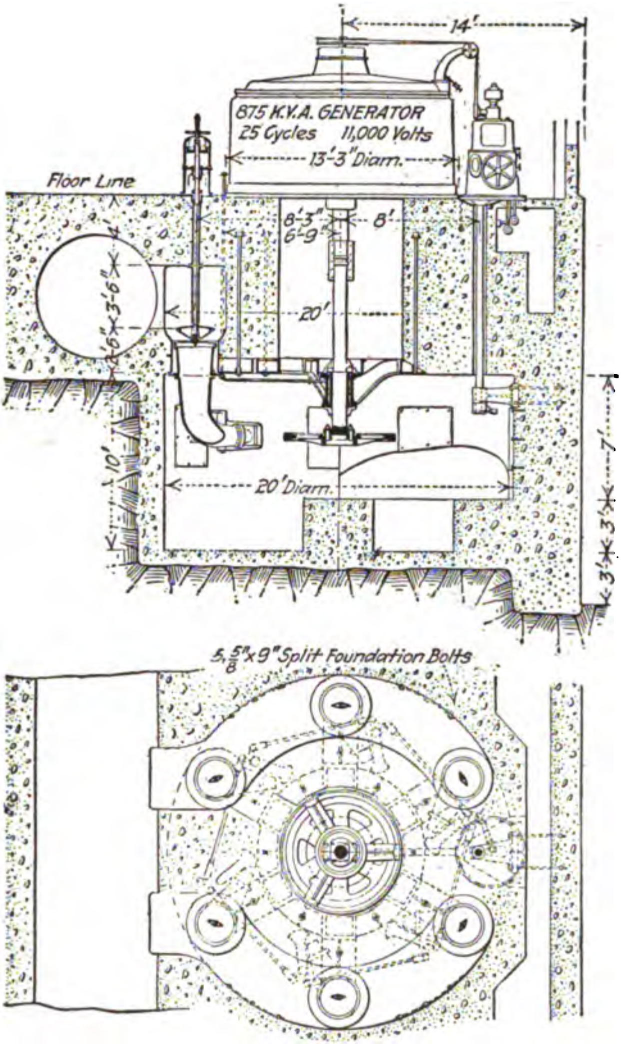


Fig. 69.—Water Wheel Designed for Silt-Laden Water

driven at 94 r. p. m. The water wheels operate under a gross head of 117 ft. The exciters are vertical units driven by Pelton-Doble wheels of the same design as the larger units and rated at 200 kw., 125 volts operating at 150 r. p. m. Under test the water wheels in this station showed an over-all efficiency of 79.26 per cent. which was in excess of the contract specification and equivalent to a wheel efficiency of 83 per cent.—*Engineering News*, April 20, 1916.

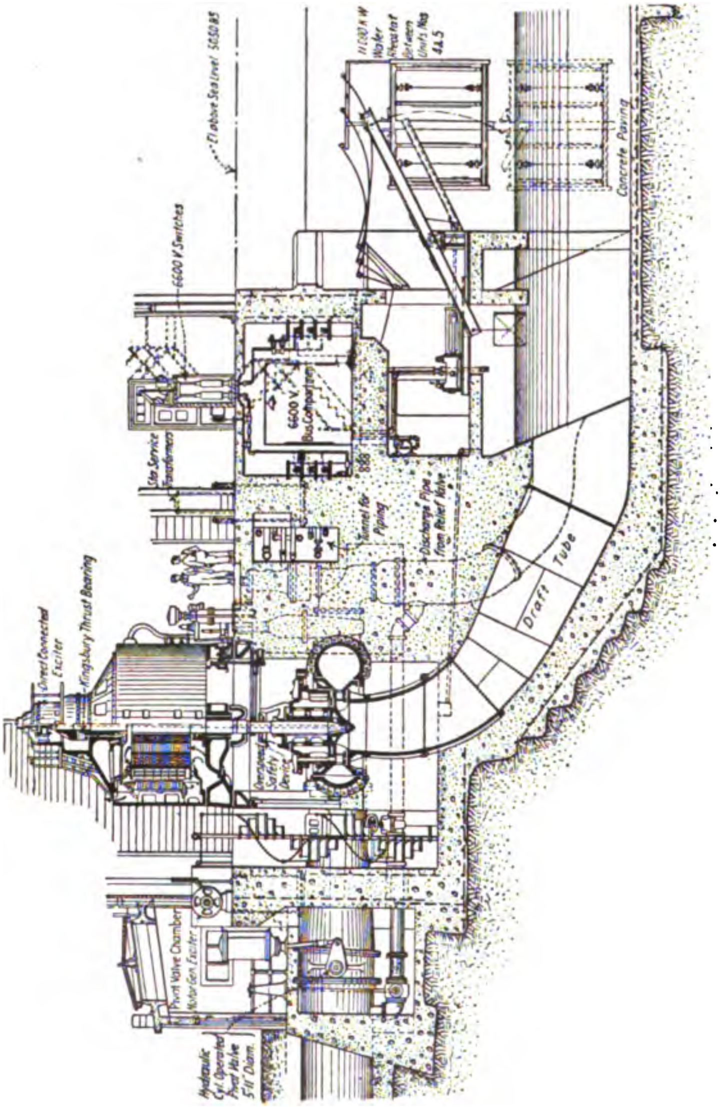


Fig. 70.—Section through 17,000 Hp. Turbine Set at Grace Station of Utah Power and Light Company on Bear River

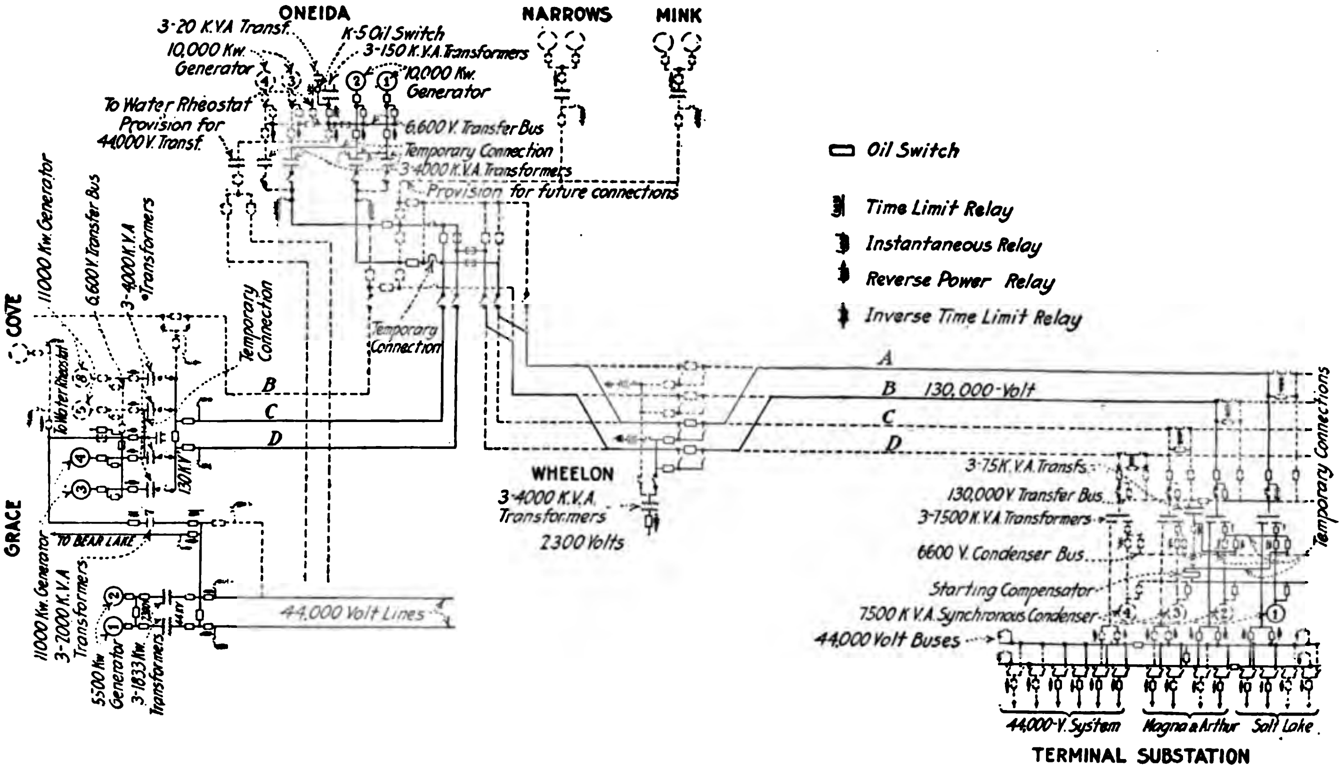


Fig. 71.—Generating and Transmission System of the Utah Power and Light Company

XXIX. GRACE STATION OF THE UTAH POWER AND LIGHT COMPANY ON THE BEAR RIVER, IDAHO

The largest generating station of the Utah Power and Light Company is located in Grace, Idaho, on the Bear River. This company operates other stations on this river at Wheelon and Oneida. The Grace plant was placed in operation in 1914 and contains three 11,000 kw. units with provisions for two additional units, making the ultimate rating 55,000 kw. The 11,000 kw. generators are driven by 17,000 vertical single runner water wheels which operated under a head of 526 ft. The energy from this plant and the other stations on the Bear River is transmitted to Salt Lake City 133 miles at a pressure of 130,000 volts, making this installation one of the notable high tension systems of this country. The company furnishes lighting and motor service to more than 100 communities and cities in Utah and Southern Idaho. It owns and operates plants rated at 120,000 kw.—*Electrical World*, June 5, 1915.

XXX. MOUNT HOOD DEVELOPMENT OF PORTLAND RAILWAY LIGHT & POWER COMPANY ON BULL RUN RIVER, NEAR PORTLAND, OREGON

The hydraulic development originally proposed consisted of three schemes, a high-head plant, an intermediate-head plant, and a low-head plant. The intermediate-head development was first constructed on the Bull Run River at such a position that it receives water from this river and the Little Sandy River. The plan called for using one power station for the intermediate and high-head developments, and the construction of a large storage reservoir to regulate the water supply for these two developments. The capacity of the reservoir is 2103 acre ft., sufficient in case of total interruption of the water supply to develop the full capacity of five turbines for 36 hours with a load-factor of 60 per cent.

The initial installation of equipment consisted of three main units each rated at 3750 kva., 60 cycles, 6600 volts, at 514 r. p. m. The generators are of Westinghouse design, each direct connected to a 6400 hp. turbine. Two of these turbines were furnished by the Platt Iron Works and one by the Wellman-Seaver-Morgan Company. Each machine is provided with bronze runners, and operates under a head of 245 ft. Each penstock is 9 ft. in diameter and placed at such an elevation that it will drain all the water from the reservoir. Although each turbine is provided with a synchronously operated relief valve, these were neglected in designing the penstocks and each will stand an impact caused by closing the turbine gates in three seconds. Immediately above the power station each penstock branches into two pipes 72 in. in diameter, and at the lower end of each branch is placed a 16 in. branch in which is placed a bursting plate to break at 250 lb. pressure per sq. in. In addition a surge tank is provided on each

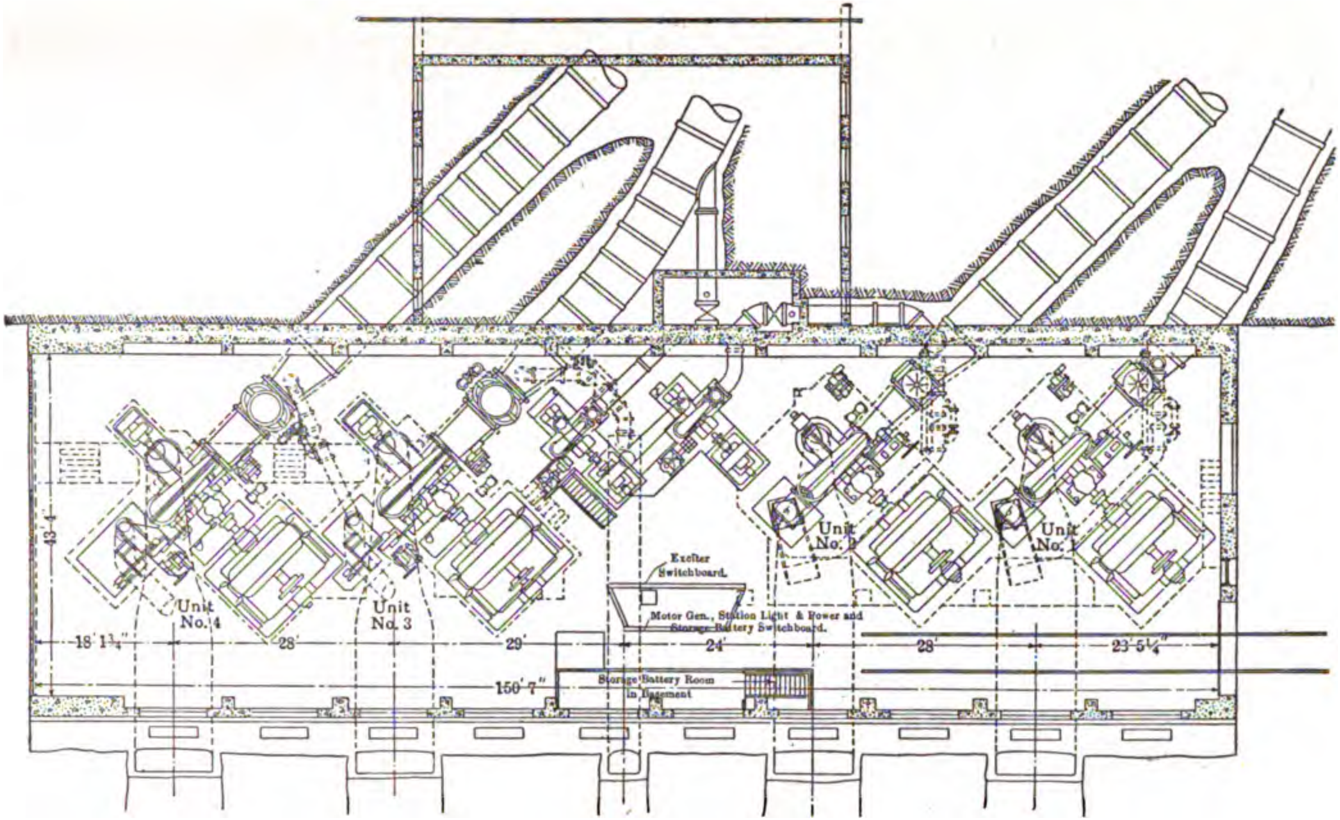


Fig. 72.—Bull Run Station of Mount Hood Railway and Power Company in Oregon

This station was built in 1911 and provides for four units consisting of 3750 kva, 60 cycle, three-phase 6600 volt Westinghouse generators operated at 514 r. p. m., direct connected to 6,400 hp. turbines operating under 245 ft. head. Two turbines were furnished by Platt Iron-Works and two by Wellman-Seaver-Morgan Company. The transmission voltage is 57,000, and 3/0 aluminum 19 strand cable is used. The station is 27.5 miles from a terminal station in Portland and 14 miles to an intersection with Oregon Water Power Railway Company.—*Electrical World*, March 29, 1913.

penstock, having a capacity sufficient to supply the needs of two machines for a period of five seconds.

A two-circuit transmission line is operated between the Bull Run plant and a terminal station in Portland, 27.5 miles, and another line from the power house to an intersection with the line of the Oregon Water Power Railway, 14 miles. Each line operates at 57,100 volts and consists of 3/0 aluminum cable (19 strands) carried on 45 ft. cedar poles, each having two cross arms with provision for a third. The poles are spaced 40 to the mile on stretches. Every tenth pole is guyed in four directions. The conductors are arranged to form a right angle triangle with two cables on the top cross arm at 4.5 ft. centers. To carry a telephone circuit a cross arm is placed 6 ft. below the future position of the lowest main cross arm to be added later. No. 12 copper-clad conductors are used for the telephone line transposed every third pole.

The system was constructed for the Mount Hood Railway & Power Company, but is now owned and operated by the Portland Railway, Light & Power Company. It was built under the direction of Messrs. Smith, Kerry and Chace.

XXXI. An Irrigation Development in Northern Utah

The generating station in Fig. 73 is a part of a 13,000 hp. development. The initial installation was 3,750 kw., consisting of one water wheel of 3750 hp. and another of 2000 hp. rating, operating under a head of 200 ft. and driving generators of 2500 kw. and 1250 kw. rating respectively.

Penstocks.—In the first 400 ft. the penstock tubes drop 173 ft., reaching the flood-plain surface, on which they are carried, practically level, for a distance of nearly 1000 ft. to the generating station. Both hillside and level are made up of sand and gravel, and on this the steel tubes are carried by about twenty saddle piers of concrete, resting directly on the gravel-bed footings. The steel penstocks vary in diameter and thickness with the normal hydrostatic head and hydraulic impact possible for the three sections. The penstock for the 3750 hp. unit is respectively 87 in., 76 in., and 65 in. diameter and 0.25 in., 0.38 in. and 0.57 in. thick for the corresponding section lengths of 520 ft. (1st), 437 ft. (2nd), and 432 ft. for the last section of penstock. The dimensions of penstock for the 2000 hp. unit are 65 in., 56 in., and 46 in. diameter, with respective thicknesses of 0.25 in., 0.38 in. and 0.44 in. for the same corresponding section lengths of pipe line, or 520, 437 and 432 ft. respectively.

The velocity of the water through the penstocks at normal turbine rating is about 6.6 ft. per second, and the friction loss a little over 4 ft. of hydraulic head, making a net head of 200 ft. available at the wheels under full load conditions. The strength of the lower sections of the penstock and the tube anchorages were designed to give a factor of safety of three when withstanding the full inertia impact of 80 per cent. rise in pressure due to closing the lower valves in three seconds. This feature, coupled with the extra precautions taken to secure close regulation of turbine speed and generator voltage, has made the use of a surge-tank unnecessary, despite the long pipe lines.

Variation in lengths of the penstock tubes with temperature changes are provided for by expansion joints with sliding sleeves and fiber packings. There are four of these joints in each pipe line, and each joint permits several inches movement. The joints are mounted on concrete foundations, firmly anchored. As a protection to the steel, the tube interiors are lined with a special preserving compound-paint. The upper lengths of the penstock are protected against inward collapse due to emptying of the tubes by suitable vents.

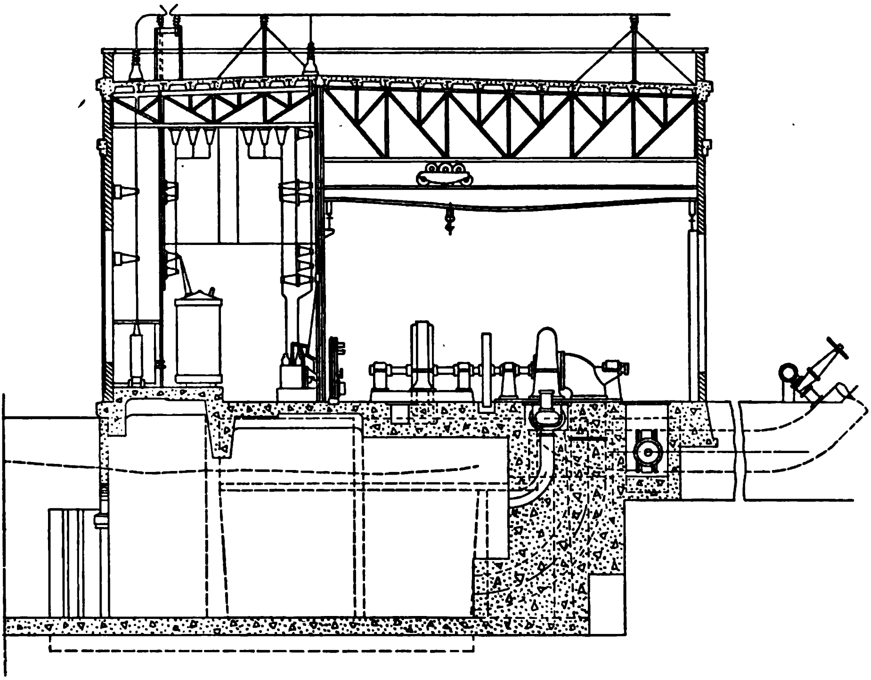


Fig. 73.—New Riverdale Plant of Davis and Weber Counties Canal Company in Northern Utah

This plant uses water from the Weber irrigation canal and provides for four units. The initial installation included two units, one 2,500 kw. and the other 1,250 kw. Each unit consisted of a horizontal inward flow reaction type single discharge Allis Chalmers water wheel driving a General Electric generator under 200 ft. head. A 3,750 hp. wheel drives the 2,500 kw. generator and a 2,000 hp. the 1,250 kw. machine each being 2,300 volts, 60 cycle, three-phase. The station furnishes energy to the Merchants Light Heat and Power Company and Salt Lake and Ogden Electric Railway Company at its switchboard. The transmission voltage is 45,000 and customers maintain their own lines. The development was erected at a cost of $45 per kw.—*Electrical World*, December 7, 1912.

Hydraulic Valves.—Entering the generating station, the supply lines are taken through hydraulic valves, 60 in. and 42 in. diameter respectively, and thence enter the reactive-type water wheels which are equipped with oil-pressure governors that regulate within 1.5 per cent. for full changes from full load to no load. Linked to the governors are synchronous relief valves which, with the closing of the turbine wickets, automatically open a by-pass discharge having a capacity 15 per cent. greater than that of the turbine itself at full load. In this way, despite sudden changes in the turbine-gate openings, the amount of water flowing in the penstock pipes is not immediately arrested, but is diverted by the by-pass channel, thus avoiding impact heads due to sudden stopping of the long moving columns of water. These synchronous relief valves are also equipped with water-saving devices which next slowly close the by-pass openings, reducing the penstock flow gradually, without rise in pressure.

Generating Units.—The water wheels are direct-connected to the generators which are three-phase designs, operating at 2,300 volts and 60 cycles. To assist in speed regulation, both units carry large flywheels. Excitation for the generators is provided by two 50 kw. direct connected machines, one driven by a 2,300 volt induction motor and the other by a small water wheel. The supply for this latter exciter is taken from a cross header outside of the generating station having valve connections to both penstock pipes so that either line can be used.

The 2,300 volt output of the generators is stepped-up to the transmission line pressure, 45,000 volts, by two groups of single-phase transformers, whose oil content is cooled by water circulation from the penstock supply. Both 2,300 volt and 45,000 volt buses are equipped with remote-control oil switches, and the outgoing high voltage lines are provided with instrument transformers for operating ammeters, voltmeters, etc. The high voltage line switches have overload protection supplied with series relays inserted directly in the 45,000 volt switch leads. Tubular copper buses are used for all 45,000 volt construction, employing 0.75 in. tubing with $\frac{1}{32}$ in. walls. The transmission line exits are made through roof-type insulators and are protected by aluminum-cell arresters with horn-gaps.

XXXII. DEVELOPMENT OF VANCOUVER ISLAND POWER COMPANY, NEAR VICTORIA, B. C.

The water power station shown in Fig. 74 is 49 ft. by 97 ft., and provides for the installation of two complete generating units, with exciters, transformers, switchboards, low- and high-voltage switches, etc. Concrete and steel were used exclusively in the construction of the building, due consideration being given to favorable location for further extension.

Pipe Line.—This generating station faces the Pacific Ocean and was erected on low ground at the foot of the pipe-line, which slopes very abruptly for the lower 300 ft. of its length. The ground surface is elevated only slightly above extreme high tide elevation, but the water wheel nozzles are placed 5.5 ft. above the maximum high-tide level. The pipe line leading from the forebay reservoir to the generating station is 9,800 ft. in length and follows a gentle slope for the greater part of its length, the lower 300 ft. descending abruptly to the station. The upper third of the length of this pipe line is designed to deliver water for two generating units of 4,000 kw. each, and consists of one riveted steel pipe 44 in. in diameter, ¼ in. to ⅜ in.

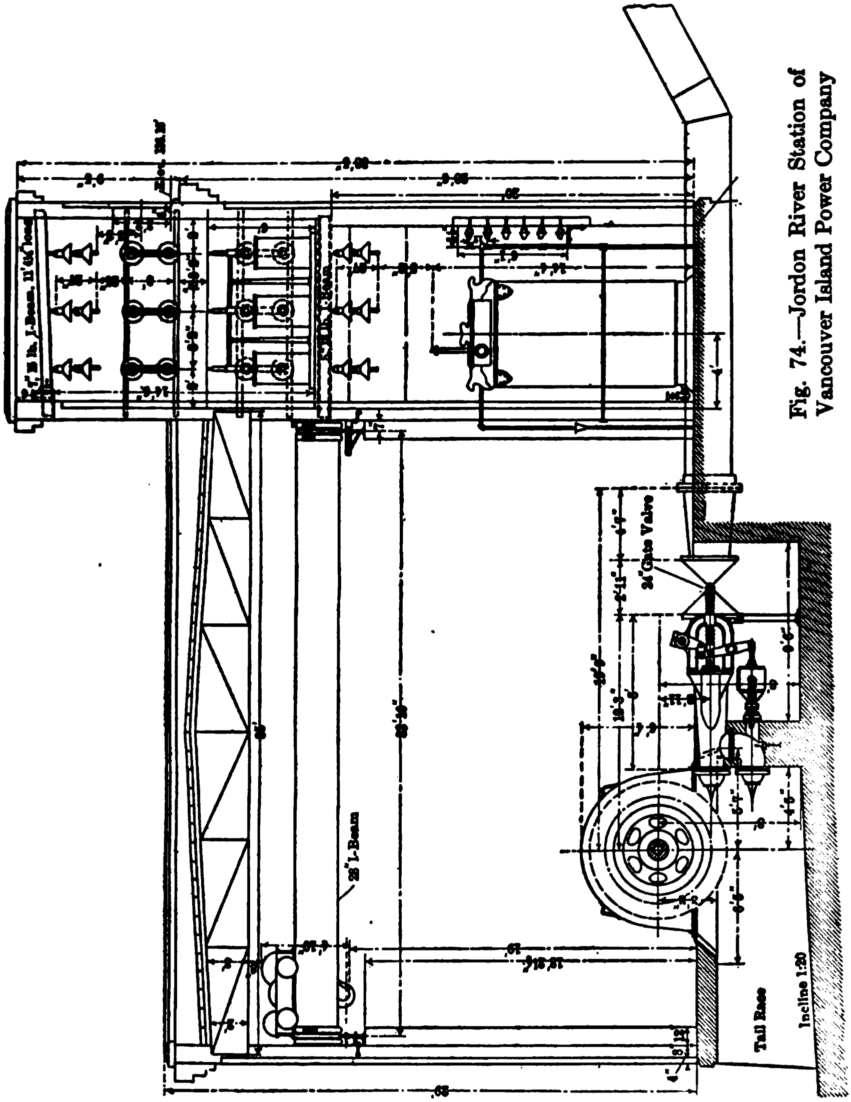


Fig. 74.—Jordon River Station of Vancouver Island Power Company

This station provides for two units consisting of 4,000 kw. generators and 6,000 hp. impulse water wheels operating at 400 r.p.m. under a head of 1,100 ft. The water wheels were furnished by McDougall Caledonian Iron Works of Montreal under Doble patents. The generators were furnished by the Allis Chalmers Company. Wynn Meredith of Sanderson and Porter was in charge of the engineering and E. E. Carpenter in charge of construction.—*Electrical World*, October 19, 1912.

plate. At the lower end of this section a cast-iron "Y" piece, fitted with two 36 in. cast-steel gate valves, is installed, providing for the extension of two lines to the generating station. The lower section of the pipe is designed to deliver water for one generating unit only, and the single line installed consists of lap-welded steel, with riveted roundabout joints, in approximately equal lengths of 36 in., 34 in., 32 in., and 30 in. diameter and varying in thickness from $\frac{5}{16}$-in. at the "Y" end to $\frac{9}{16}$-in. at the lower end. To prevent failure as in the case of a similar lapwelded pipe elsewhere, the lower end of the pipe line for a distance of 2,200 ft. was reinforced by 1 in. round steel bands, after the manner of a woodstave pipe, with spacing from 3.5 in. to 4 in. Eight 4 in. air valves and four manholes were installed along the length of the pipe, and immediately back of the generating station a cluster of four automatic pressure relief valves were installed. Concrete anchor blocks and supporting piers were erected at proper intervals along the pipe line.

This pipe line enters the generating station at the back and is connected to the generating units through a 24 in. gate valve, there being an effective head of 1,100 ft. The water is controlled by a needle regulating nozzle in conjunction with an auxiliary needle nozzle, the needle of which is mechanically connected to the main needle and is so arranged that it opens automatically as soon as the main needle closes rapidly or beyond a certain predetermined point. In this way the auxiliary nozzle maintains a sufficient vent to avoid a dangerous rise of pressure in the pipe line. The auxiliary nozzle is also fitted with an independent slow-moving adjustable time-element mechanism which gradually closes the nozzle when the main needle stops moving, thus conserving the water supply. An oil pressure governor for speed regulation is directly attached to the main nozzle needle.

Generating Units.—The main generating units consist of two 4,000 kw. alternators and two 6,000 hp. impulse water wheels. The units are of the two bearing type, having the revolving field of the generator mounted on the shaft between the bearings and the exciter wheel overhanging at one end. The speed is 400 r. p. m. One exciter is installed of sufficient size to supply maximum field current for the two generating units. The extended shaft carries on one end an overhanging impulse water wheel and is connected at the other end to an induction motor, which operates at the generator voltage and drives the exciter generator continuously. The exciter water wheel is equipped with hand control only, as the motor serves as a speed regulator and no governor is necessary.

The energy delivered by the generators at 2,300 volts is stepped up to 40,000 volts by means of three 1,400 kva., oil-insulated, water-cooled single-phase transformers, which are installed in fireproof compartments back of the generators. These transformers are now operating in delta connection, delivering current to the transmission line at 40,000 volts.

This voltage will eventually be raised to 60,000 volts by changing the delta connection to star connection with grounded neutral. No. 2/0 aluminum seven strand cable is used on wood poles with steel cross arms, spaced 300 to 400 ft.

XXXIII. Development of Great Northern Power Company at Duluth, Minn.

The water supply for the station shown in Fig. 75 is received through a tunnel nearly three miles long which diverts the water that normally flows around the bend of a large river. A heavy concrete dam was erected at the intake which will ultimately have a height of 140 ft. The completed installation is designed for an available water head of 535 ft.

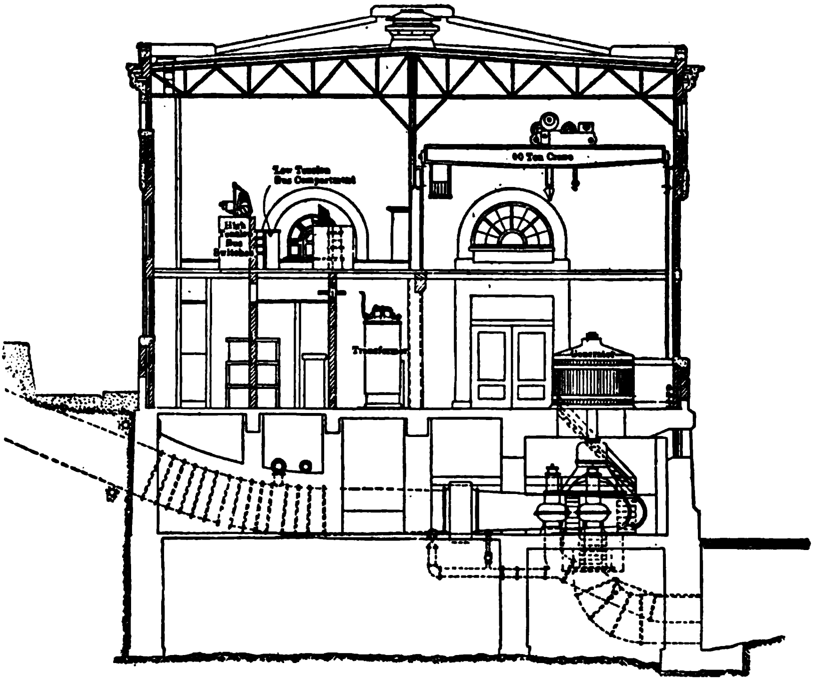


Fig. 75.—Station of Great Northern Power Company at Duluth, Minn.

This station furnishes energy in bulk to metallurgical and industrial plants around Duluth. It contains four generating units each consisting of an 18,000 hp. inward flow Francis turbine direct connected to a vertical shaft revolving field generator rated at 10,000 kw. and operating at 400 r. p. m. The unit is three-phase, 11,000 volt, and at the time of installation in 1906 was the largest constructed. The transmission voltage is 110,000 volts.

Turbines.—The four main water wheels installed are inward flow Francis type turbines and in point of output are among the largest, being rated at 18,000 hp. each. The water for each unit is carried through a separate steel feed pipe 450 ft. in length from the mouth of the tunnel to the generating station and controlled by a motor-operated gate-valve at the head of the steel pipe. The vertical shaft carrying the turbine and the revolving field of the generator is supported on an oil disk step-bearing located between the wheel and the generator. A triplex pump in the turbine chamber supplies oil to the step-bearings under 215 lbs. pressure and a second pump, operated by an electric motor, supplies oil at the same pressure for operating the governor cylinders. These governors are placed on the main floor and are of special design, known as the double float lever type.

Generators.—The main generators at the time of installation in 1906 were the largest of their kind ever constructed. They are of the vertical shaft revolving field type rated at 10,000 kw. delivering three-phase 60 cycle current at 11,000 volts. The stationary armature is supported directly on the main floor structure. The revolving element is supported by two guide-bearings, one above and one below the revolving field. The rotor was especially designed for this installation and before shipment was tested at double its normal speed of 400 r. p. m. Two exciter sets are provided each of 250 kw. capacity at 250 volts. These machines are of the horizontal type direct-connected to 350 hp. water wheels.

Each generator feeds directly through cables in the ducts under the main floor and the remote control oil switches on the second floor, to a three-phase transformer having a normal capacity of 10,000 kva. stepping up from 11,000 volts to 110,000 volts delta. The generator circuits and the outgoing transmission lines are controlled from the main switchboard in the balcony. This switchboard is of the standard bench-board type with panels for each generator and its transformer and for the outgoing transmission lines.

XXXIV. RAINBOW FALLS DEVELOPMENT ON MISSOURI RIVER AT GREAT FALLS, MONTANA

The Rainbow Falls development at Great Falls, Montana, on the Missouri River was completed in July, 1910. At this time, six generating units with a total rated capacity of 21,000 kw. were placed in service. Each of the 3,500 kw. generators is direct connected to a 6,000 hp. turbine of the inward flow Francis type operating under a 105 ft. head. The output of two of these units is utilized in the vicinity of Great Falls and is transmitted at the generator voltage of 6,600. The power from the other four units is stepped up to 102,000 volts delta through four banks of single-phase transformers rated at 3,600 kva. per bank. Energy is transmitted at this voltage to Butte, Montana, a distance of 130 miles, over two separate parallel lines constructed on the same right of way. The transmission line towers, which were employed all carry two ground wires besides the high voltage lines. At the Butte substation four 3,600 kva. banks of transformers are installed, stepping down to 2,500 volts for the synchronous and induction motor load.

An extension of the transmission line 22 miles beyond the Butte substation supplies power at 102,000 volts to Anaconda where it is used for the operation of the Washoe Smelter. The initial equipment of the Anaconda substation included three 1200 kva. transformers controlled by a K-15, 100,000 volt oil switch and protected by an electrolytic lightning arrester. This equipment was later increased to six transformers, making two complete banks with a total capacity of 7200 kva.

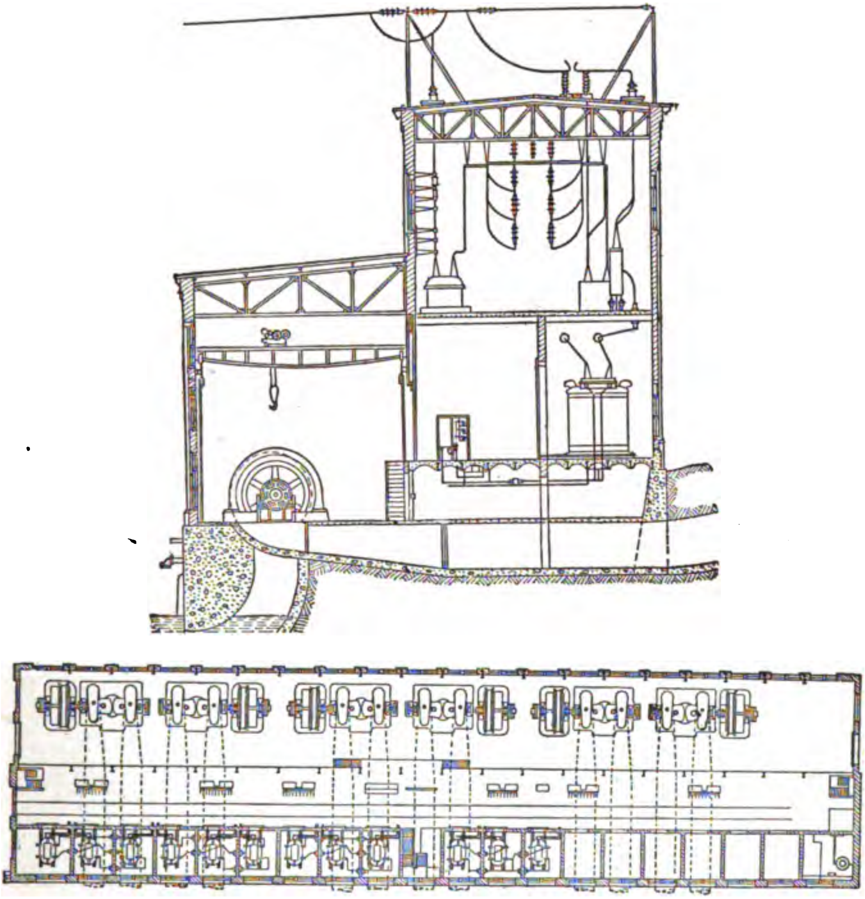


Fig. 76.—Section Through Rainbow Falls Station on Missouri River Rated at 21,000 Kw. and Operating under 105 Ft. Head

All transformers and switching apparatus as well as generators were furnished by the General Electric Company.

XXXV. HYDROELECTRIC DEVELOPMENT ON THE CONNECTICUT RIVER NEAR BRATTLEBORO, VERMONT

A typical low-head development which is one of the largest single hydraulic stations in New England is located on the Connecticut River at Vernon, six miles below Brattleboro, Vermont. The generating equipment of this station comprises eight 2,500 kw. generators driven by specially

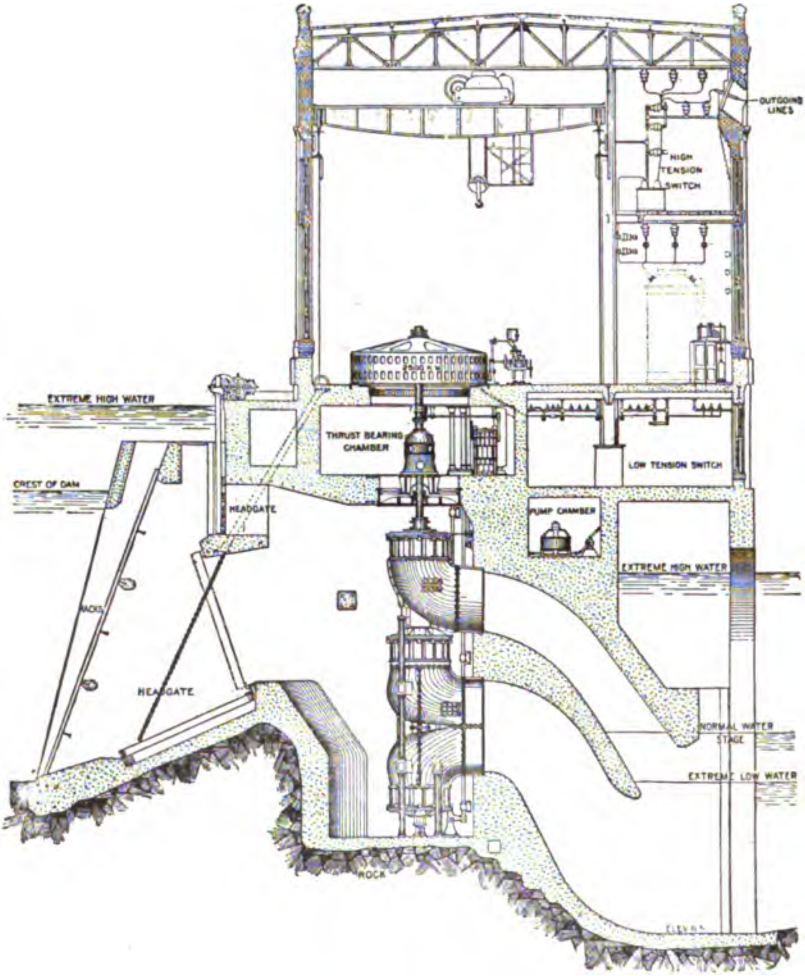


Fig. 77.—Section Through Connecticut River Power Station at Vernon, Vt.

This station was built in 1910 and at the time was the largest single hydroelectric plant in New England. It contains eight 2,500 kw. generators driven by vertical turbines each having three runners. Two of these which are 60 in. in diameter are used for normal operation, the third a 57 in. runner is used for high water and normally runs idle. Under these conditions the units operate under a head of from 32 to 34 ft. Energy is transmitted at 66,000 volts to Worhester, Mass., a distance of 66 miles. Service is furnished to cotton mills, paper mills and local power and traction companies. The station equipment is of General Electric design.

designed vertical turbines operating under a head of from 32 to 34 ft. These wheels consist of two 60 in. runners for normal operation and a 57 in. runner which ordinarily runs idle but can be utilized under high water conditions.

Current is generated at 2,300 volts 60 cycles, and is stepped up through three-phase transformers to the transmission voltage. Four 5,000 kva. oil-cooled transformers raise the voltage from 2,300 to 66,000 volts Y for transmission over two independent lines to Worcester and intermediate towns, a distance of 66 miles. A 2,500 kva. three-phase transformer wound for 2300/31,500 volts supplies current to a 20 mile transmission into Keene, New Hampshire, and to the city of Brattleboro, Vermont. These two lines are at present supplied at 19,100 volts. A fifth feeder supplies the town of Vernon with power and lights at 2,300 volts.

The switchboard is of the remote control type and consists of 19 marine finished slate panels. On the front of this board is mounted a dummy busbar giving in miniature all of the station connections. A type TA voltage regulator is installed on one end of the board and a storage battery panel on the other. The storage battery is used for the switch signal lights and for operating the remote controlled oil switches. An emergency connection from the exciters is also provided for this purpose.

The general scheme of wiring is sufficiently flexible to permit of all desired combinations. Two generators and one 5,000 kva. transformer comprise one complete unit capable of being isolated on any line or busbar or of being operated in parallel with other units. This arrangement also permits of any generator being connected through any transformer.

Substations along the main 66,000 volt transmission and at the Worcester terminal contain step-down transformers with a combined rating of 24,000 kva. These stations supply energy for the operation of cotton and paper mills and many other industrial plants as well as for local power and traction companies. With many of these customers reciprocal contracts are maintained providing for the purchase of power from isolated steam plants in case of low water at the generating station.

XXXVI. Lock 12 Development of Alabama Power Company on Coosa River

The site of the Lock 12 development onthe Coosa River, is in the central part of Alabama and the dam is one of a series planned by the United States government in conjunction with locks to make the Coosa River navigable. The Lock 12 dam is built of cyclopean concrete. It is 1,563 ft. long from shore to shore and the top of the spillway gates are 72 ft. above the water in the tailrace. The spillways are in 26 sections, each section being separated by concrete piers on top of which is a track for a special traveling hoist to be used in raising and lowering the spillway gates. These gates are 14 ft.

high, 26 ft. wide and slide up and down in vertical grooves in the spillway piers. They can be operated by either an electric hoist or by a steam hoist. Motive power to operate the gates is transmitted from the hoist through a wabbler connection to a shaft and gears operating a horizontal shaft that winds and unwinds flexible flat steel cables. Two of these cables are attached to each gate and each gate raises and lowers independently of the others. The hoist can be moved along the track the full length of the spillway and coupled to any gate. This allows the level of the pond to be regulated by passing the surplus water through the gates during the high water and holding back the required amount during low water periods.

Power House.—The power house structure is located near the west end of the dam and is built into the lower side of it. In front of the power house are the penstock gates, of which there are two for each turbine. These gates are operated by hydraulic cylinders mounted directly over them and are direct connected to the hydraulic piston rods. The pistons are operated by oil pressure from the governor pressure pumps. Under normal conditions these gates are left open and held open by mechanical devices, thereby taking their weight off of the cylinders and relieving the governor pumps of this work. If it is necessary to close the gates in emergency the mechanical devices can be tripped and the oil in the cylinders bypassed from the bottom to the top of the pistons letting the gates down quickly but without any slack.

In front of the power house and running the full length of it is a gantry crane running on tracks laid on top of the dam. The crane overhangs the water in the forebay so that it can handle the racks and screens in front of the penstock gates. It also served to pick up freight and material from the barge which carries freight from the company's freight depot at Ida about 12 miles up the river. This barge is towed by a gasoline tug.

The lower floor of the station is occupied by the generators, governors, governor pumps, an overhead traveling crane, and other auxiliary apparatus. On the north side of the generator room is the switchboard gallery, low tension 6,600 volt bus structure and oil switches, station power and lighting transformers, a motor generator exciter, battery charging set, telephone booth, and lavatory and locker rooms. This gallery is directly over the lower slope of the dam and elevated above the generators, giving a clear view of all the generators from the switchboard. Directly above the switchboard gallery, and of the same width, is the transformer room which is separated from the generator room by a brick partition. Between this floor and the switchboard gallery is a mezzanine floor which is occupied by the superintendent's office and a store room. Located on the top floor are the 110,000 volt oil switches and buses, storage battery room and oil tanks for bearing and transil oil. The part of this room that is above the transformer room is open to allow the high tension leads from the step-up transformers to be brought up to the 110,000 volt bus structure and oil switches. The space on the roof is occupied by lightning arresters and transmission line terminals. Three high tension circuits enter the building through roof bushings and connect to the high tension buses through oil switches.

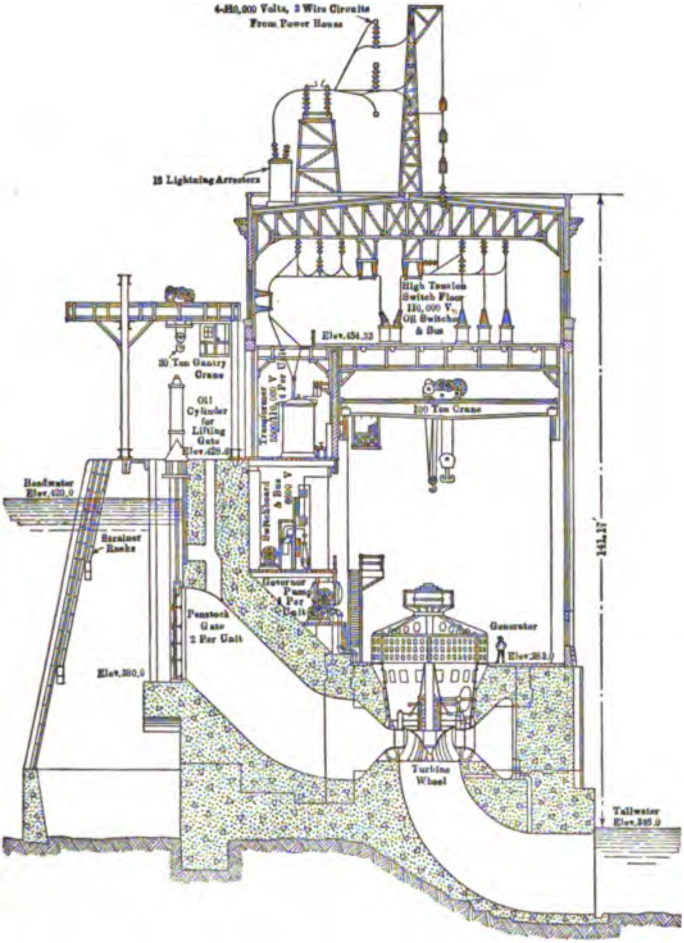


Fig. 78.—Lock 12 Station of Alabama Power Company on Coosa River

This station provides for an ultimate installation of six 17,500 hp. single runner turbines operating under a head of 68 ft. and driving 13,500 kva., 6,600 volt, 60 cycle generators at 100 r. p. m. It is the main generating station for a 110,000 transmission system that serves the principal industrial districts of the State of Alabama, and is 50 miles from Birmingham where connection is made with the local system through a large outdoor substation. The Lock 12 station was placed in operation in July, 1914. The water wheels are of the Francis reaction design built by the I. P. Morris Company and when installed were the largest single runner units ever made measuring 13 ft. 3 in. in diameter. The generators are of Westinghouse design and the switches and switchboard furnished by the General Electric Company. The engineering work was done by the company's corps of engineers headed by E. A. Yates as chief engineer, E. L. Sayer, assistant chief engineer, W. E. Mitchell, electrical engineer, and O. G. Thurlow, designing engineer.

Generating Units.—Four 13,500 kva., 6,600 volt, 60 cycles, Westinghouse vertical generators were installed, with provision made for two more future units. Each machine has its own direct connected exciter. These exciters have a capacity of 150 kw. at 250 volts. Besides these exciters there is one 150 kw. 250 volt spare exciter driven by a 440 volt 225 horsepower induction motor. This exciter may be used on any one of the four generators.

The generators are driven at 100 r. p. m. by 17,500 horse power Francis reaction single runner turbines, built by the I. P. Morris Company. Water is brought to each turbine through rotating vanes from a snail shaped scroll casing, which curves around the periphercy of the water wheel. Water from the head gates enters one end of this scroll casing through two short concrete tunnels. These turbines pass approximately 2,500 cubic feet of water per second when the generator is operating at its rated capacity. The head is 68 ft.

Speed is controlled by Lombard governors having a capacity of 250,000 foot pounds at 200 pounds pressure. The minimum time element of course is two seconds. The fly wheel effect of the generator rotor alone is 12,500,000 foot pounds.

The entire weight of the turbine and rotating parts of the generator and exciter is supported by 42 in. Kingsbury bearings, which are placed between the generator and exciter. Oil for these bearings flows by gravity from two oil tanks on the top floor of the building to a large pan surrounding the bearing. When the oil leaves the bearings it is discharged by gravity into two tanks in the basement, where it is cooled by water circulating in cooling coils therein. Two triplex pumps pump the oil from these tanks back to the tanks on the top floor whence it flows through the bearing again. These pumps are geared to and driven by a 5 horse power, 440 volt, 1,150 revolutions per minute induction motors. Alignment of the big generator shaft is maintained by water cooled lignum vitae guide bearings mounted between the generator and water turbine.

Transmission System.—The 110,000 volt transmission system of the Alabama Power Company serves the principal industrial districts of the State. There are 92 miles of double circuit and 94 miles of single circuit steel tower lines. No. 2/0 medium hard drawn copper was chosen for conductors based upon about 12 per cent. loss at ordinary power factors for 100 miles of single circuit No. 2/0 line. These conductors were strung at such tension that under the most severe weather condition of Alabama, zero deg. Fahr., ¼ in. of ice coating, and a wind of 70 miles per hour, a strain of only one-half the ultimate strength of the cables would be produced. The lines are supported on double circuit, four-legged steel towers of an average weight of 4,700 lbs. The height from the earth to the lowest cross-arm was made sufficient to use these towers on a spacing of approximately 750 ft. and yet have a clearance above ground in the center of the span of 25 ft. The vertical spacing of cross arms is 10 ft. with a horizontal spacing between circuits of 15 ft., the middle cross-arm being somewhat longer than the other two to prevent short circuits due to whipping or ice loads.

Six disc strings of the 10 in. corrugated and the 12 in. flat insulators were originally installed on suspension and seven of these discs at the strain points. Later an extra disc per string was added to increase the factor of safety of these strings on account of the unevenness of matching the units in the strings. The lightning storms of Alabama are particularly severe. To guard against interruptions from this source two steel wires grounded directly at each tower were used over the transmission conductors. No plates or rods driven into the earth were needed to secure a good conducting medium to care for the lightning discharges as the large area of steel grillages in the tower footings in fairly moist earth proved of relatively low resistance. All the 110,000 volt tower lines and 22,000 volt distribution lines are provided with electrolytic lightning arresters in addition to the ground wires along the lines.

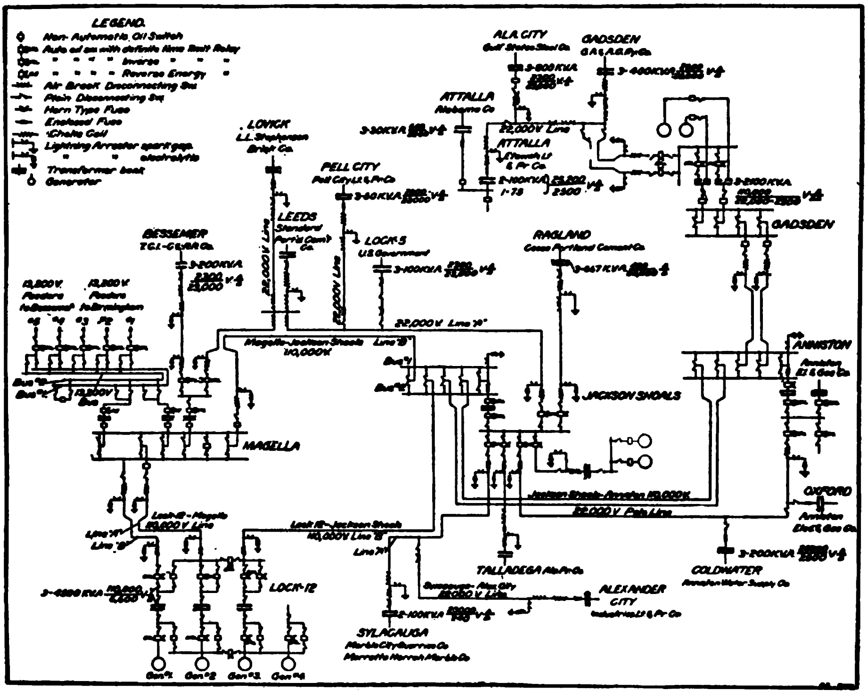


Fig. 79.—Layout of Generating and Substations and Transmission System of Alabama Power Company

XXXVII. DEVELOPMENT OF THE TALLASSEE POWER COMPANY ON THE YADKIN RIVER AT BADEN, N. C.

The hydroelectric development near Baden, N. C., is of considerable historic interest on account of the changes in construction plans through three changes in promoters of the scheme. The work was originally started in 1901 when George Whitney, with Pittsburgh capital, started an elaborate cut-stone masonry dam about 38 ft. high, 4½ miles above the Narrows on the Yadkin River, near Baden, N. C., the location of the final dam. This work was abandoned in 1910 and except for salvage of stone for later construction was a complete loss estimated at $3,000,000. In 1912 the Southern Aluminum Company, controlled by French capital, started work on a new high dam at the Narrows with plans to build a station for the development of 90,000 hp. The French engineers placed the power house on the west side of the river and designed it for twin runner center discharge turbines on horizontal shafts. These turbines were to be direct connected to direct current, 520 volt, generators rated at 5,200 kw., arrangements being made for 18 of these units and two alternating current units of 1200 kw. each. The initial installation called for the use of five double turbines and generators.

The French engineers provided for flood flow by designing two vertical wells 60 ft. in diameter connecting to rectangular twin tunnels 40 ft. wide and 34 ft. high driven in the side-hill rock on the east side of the river and used as diversion channels during the construction of the dam. These were completed by the construction company, timber and rock cofferdams were built, the power-house foundations of concrete completed, the steel frame erected, and about 50,000 yds. of cyclopean concrete placed in the dam on the west side, using a 1 : 3 : 5 mix. When the war broke out in 1914 all work ceased on account of war conditions.

The Tallassee Power Company bought out the French company in 1914, and began work on the completion of the project in January, 1916. This company's engineer decided to use the part of the dam already completed, but to abandon entirely the original power house and flood-water provisions of the French engineers, just described. It was felt that the French engineers did not provide for a large enough flood and that the tunnels were unsafe. Hence it was necessary to build the bypass and also provide for part of the floods by a spillway over the dam. The old power house was only 20 ft. from the toe of the dam, entirely too close for safety, as the standing wave below the dam would wreck the foundations. The French engineers did not contemplate passing any water over the dam, so that the old power-house location was satisfactory for such conditions. The discharge from the tunnels during floods would interfere with the flow of water that passed over the dam, and this would cause a dangerous rise of water in the river

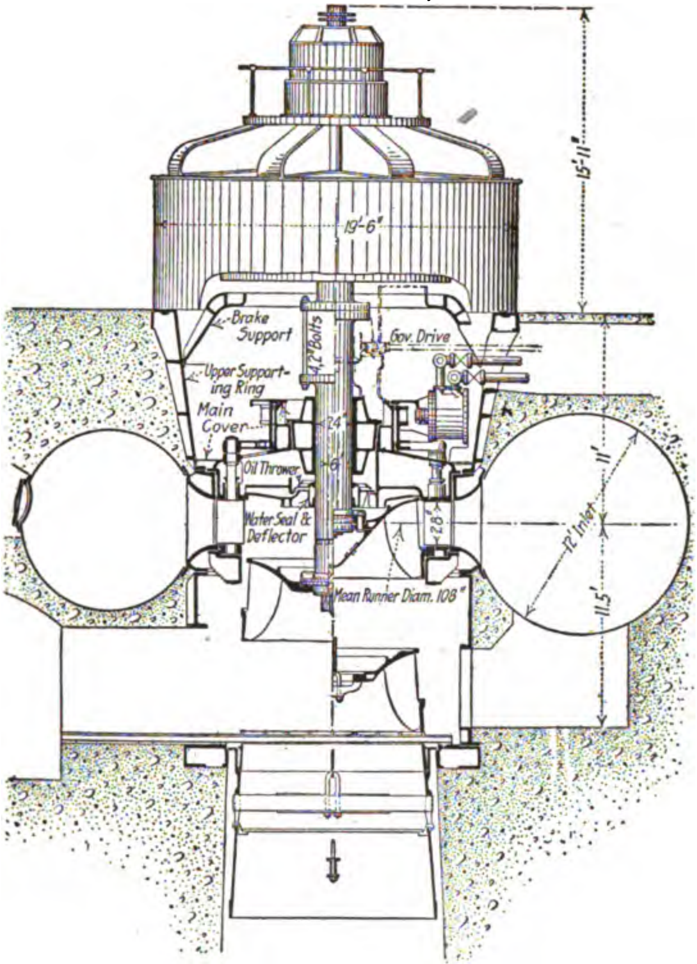


Fig. 80.—Section Through 31,000 Hp. Unit in Yadkin River Station of Tallassee Power Company, Baden, N. C.

This turbine is rated at 31,000 hp. under a head of 180 ft., at 154 r. p. m., and is one of three comprising the initial installation of the Tallassee Power Company at its Yadkin River development at Baden, N. C. It is the largest single runner Francis unit built to date (1916). The direct connected 13,200 volt generator is rated at 18,000 kva. The Badin plant is of especial interest on account of the fact that work on the plans was started in 1901 and has been in the public eye as a proposition of wonderment on account of the capital invested and never used. With an idea of securing abundant hydroelectric power one elaborately constructed dam of cut stone was built and abandoned at the cost of around $3,000,000 and a new structure started which will cost around $2,000,000. French capital was largely involved until the site and property was purchased by the Aluminum Company of America in 1914. The initial installation worked up by the French company known as the Southern Aluminum Company is of special interest since it called for five double water wheels direct-connected to direct-current 520 volt, generators of 5,200 kw. each, with arrangements for eighteen of these units and two alternating-current units of 1,200 kw. each. These units were purchased and ready for installation when the property was taken over by the Aluminum Company of America. The 5,200 kw. generators have been remodeled as rotary converters to operate on the frequency of the generating system of 36 cycles. Details of final installation were published in the *Engineering Record*, November 18, 1916, and the *Engineering News*, November 16, 1916.

opposite the old power house and would have wrecked it had the old scheme of using the tunnels been adopted. This view of the French engineers' inadequate provision for floods was vindicated when the 1916 flood, which was about 25 per cent. greater than the maximum flood assumed by them, wrecked their power-house foundation.

Design of Dam.—Although curved in plan to a radius of 1,678 ft. and supported by rock foundations on the sidehill, arch action was not considered in the dam design. Vertical contraction joints in a radial direction are introduced by constructing alternate blocks 45 to 50 ft. long, each block designed as a pure gravity section. At the ends of the dam the downstream face is curved to throw the water toward the central stream bed. Bonding grooves between the blocks are spaced about 5 ft. apart, and the concrete surface is painted with tar to prevent adhesion, thus insuring contraction cracks in a vertical plane and preventing any possibility of interior uplift on diagonal cracks developed by contraction. Drain holes and inspection galleries were introduced near the up-stream face of the dam.

New Power House.—The new power house, placed on the east side of the river, is 180 ft. long and 57 ft. wide as before, so that the old steel frame could be used again, the columns being reinforced by steel channels on the inside. The foundations were entirely remodeled to conform to vertical-shaft turbines direct-connected to alternating-current 13,200 volt, 36 cycle generators of 18,000 kva. each, three units being installed first and one unit later. The 5,200 kw. direct-current 520 volt generators for the original power house were remodeled into rotary converters, a change which necessitated the odd frequency of 36 cycles.

The power station for many reasons is one of the most interesting built in recent years. By generating at the transmission voltage, namely, 13,200, no station transformers are required except for the building services. This has greatly simplified the switching layout and the effect has been increased by using outdoor type of main oil switches on a gallery outside the generating station. Copper cables in conduits carry the conductors from the generators to oil switch terminals.

The remarkably steady load to be furnished by the nearby aluminum works permits an efficient use of the very large generating units which are larger than commonly desirable in general practice. Each turbine will develop 27,000 hp. at maximum efficiency and 31,000 hp. at full gate so that in point of rating these are the largest hydraulic turbines ever built. Each turbine drives an 18,000 kva., 36 cycle, 13,200 volt, three-phase generator with its exciter mounted on the top. Aside from this, there are points of interest in mechanical design, notably the use of steel-plate scroll casings embedded in concrete and a scheme of dismantling the runner from below as shown in the accompanying illustration. The runner diameter is 108 in., the speed 154 r. p. m. and the head 165 to 180 ft. The casing inlet is 12 ft. in diameter and a tapering thimble connects to the 15 ft. penstock. The upper part of the draft tube is of cast iron and telescopes into the section below, which is molded in the concrete substructure. The draft tube is 7 ft. in diameter at the top but immediately begins to flare, flattening as it makes the usual right angle turn with the outlet 32 ft. wide by 13 ft. 3 in. high.

Ratings of Turbines and Generators.—As the head available for the operation of these units will vary considerably two guarantees of outputs at given heads were made. Each unit is designed to deliver to the generator shaft not less than 27,000 hp. when operating under an effective head of 165 ft. and a speed of 154 r. p. m. Under these conditions it will develop an efficiency of not less than 90.5 per cent., efficiency being defined as ratio of water horsepower delivered to the unit to mechanical horsepower output at the turbine shaft. Each unit also is guaranteed to deliver not less than 31,000 hp. operating under an effective head of 180 ft. and at 154 r. p. m. Tests on a 32-in model runner conducted at Holyoke, Mass., showed an efficiency of practically 91 per cent.

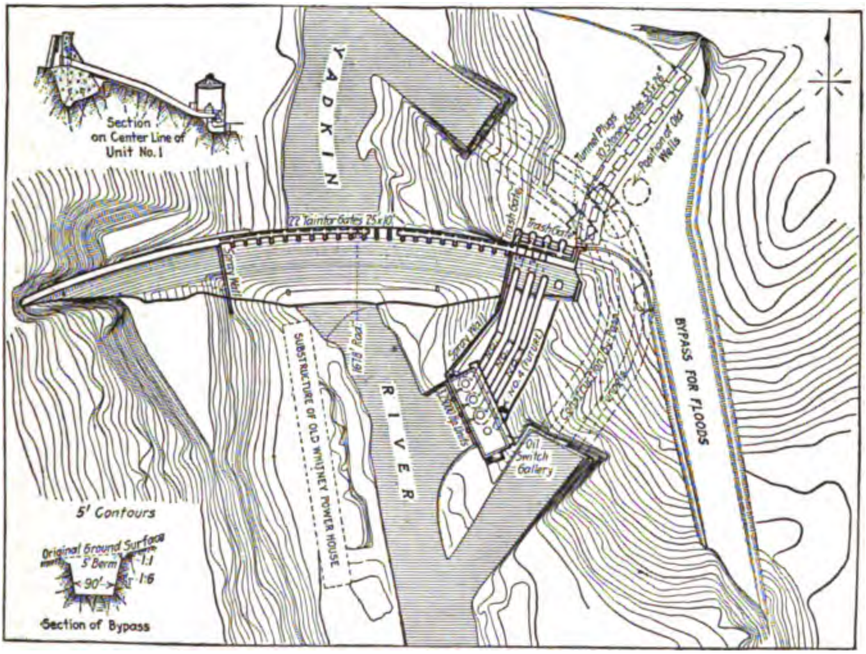


Fig. 81.—Locations of Old and New Power Houses, Tunnels and Wells of the Earlier and Final Designs for Yadkin River Development

The generators for these units are 28 pole, 13,200 volt machines rated at 18,000 kva. They have, however, an overload guarantee of 22,500 kw. at unity power factor. The efficiency at 18,000 kw. and unity power factor is 96.9 per cent. The stator is 19 ft. 6 in. in diameter and the rotor 14 ft. 9 in. The rotor flywheel effect (WR^2) is approximately 4,000,000. The weight of the rotor of both generator and exciter is 146,000 lbs. and includes that of the bridge between generator frame and exciter. The latter is a 72 kw. 250 volt machine.

The turbine runner weighing 20,000 lbs. is a single piece of solid bronze and is probably the largest casting of its kind ever made. The turbine shaft weighs 18,000 lbs. The total weight of the revolving parts and the reaction thrust of the loaded runner are carried by Kingsbury thrust bearings. The governor is essentially the standard design of the wheel manufacturer in which fly-ball actuated valves control the admission and discharge of oil to two operating cylinders, (servomotors) that have piston rods running to the shifting rings.

The turbines were designed, built and installed by the Allis-Chalmers Manufacturing Company of Milwaukee, Wis., under the direction of W. M. White, chief engineer. The generators and exciters were furnished by the General Electric Company, Schenectady, N. Y. The installation of the Tallassee Power Company at Baden, N. C., was designed under Edwin S. Fickes, chief engineer, and G. F. Murphy, principal assistant. William Hoopes is chief electrical engineer, and T. J. Bostwick, principal assistant. The hydraulic development was designed by J. W. Rickey, chief hydraulic engineer, and C. B. Hawley, assistant. J. E. S. Thorpe was resident engineer for the power company.

XXXVIII. THE 65,000 HP., 1,375 FT. HEAD DRUM DEVELOPMENT OF PACIFIC GAS AND ELECTRIC COMPANY

The storage capacity of the lake for this development, with a 225 ft. dam, is 44,000 acre ft., or about 14,000,000 gal. The ultimate dam is 305 ft. from water surface and 320 ft. above bedrock, making it one of the highest from water surface. From storage the water is brought through a 4,456 ft. tunnel in solid granite, 1,100 ft. of which is concrete-lined, the finished size being 8 ft. 8 in. in diameter. An aqueduct 8.4 miles long carries the water from the tunnel to the forebay, which is a large regulating reservoir having a capacity of 425 acre ft. This insures continuous service at the power station by carrying the fluctuations between water supply and electrical load, as well as bridging any interruption in the canal system upstream.

The drop from the forebay to the nozzles of the impulse wheels is 1,375 ft. A steel penstock or pressure pipe line (two lines eventually), 72 in. in diameter by 1/4 in. thick at the forebay and tapering according to pressure to 52 in. diameter by 1 1/4 in. thick at the power house, is the connecting link. The power station is located in a deep gorge. To find a site for the power house it was necessary to sluice by means of the hydraulic monitor some

40,000 cu. yd. of hill slope, excavating finally by blasting into solid serpentine. The site is about 125 ft. by 500 ft. in size. The building is of reinforced-concrete and structural-steel structure, 77 ft. 6 in. wide by 208 ft. 8 in. long and 65 ft. high.

Generating Units.—The four 12,500 kva. generators now operating are 6,600 volts, three-phase, 60 cycle, 20 pole machines. They are the revolving field type, horizontally divided, the armature being star-connected. The speed of the machines is 360 r. p. m. The shafts of the armatures are horizontal, built with enlarged ends upset 2 in. for the reception of the overhung water wheel runners. At each end of the shaft an impulse water wheel of 9,000 hp. is overhung beyond the bearings. The maximum diameter of the shaft through the rotor is 26¼ in., and 18 in. at the bearings, which are 60 in. each in length. The over-all length of the shaft is 24 ft. 8¼ in. and its weight 26,420 lbs. The diameter of the pitch circle of the water wheel, which has 17 double buckets attached thereto, is 85 in. Each wheel is driven by a single deflecting jet. Its size is controlled with a needle valve, and the jet at maximum rating is 6⅞ in. in diameter.

Governors.—Governing is effected by a special oil-pressure operated, relay-valve-type horizontal governor, which operates the deflecting nozzle directly. The body of the nozzle is 8½ in. inside diameter at the jet, opening and increasing to 26 in. at the ball joint. It is counterbalanced with a hydraulic piston. The speed drop for gradual increase from no load to full load is adjustable from zero per cent. to 2 per cent. An electrical distance speed-control device operated from the switchboard by 125 volt direct current is provided. This enables the operator to vary the speed from 5 per cent. above to 15 per cent. below normal speed. A hand emergency control is mounted so as to revolve freely on a threaded piston rod, which can be connected with or disconnected from the piston rod by means of a split bronze nut locked by suitable lever mechanism. An operator at the regular hand wheel can easily exert the full output of the governor, which is 20,000 ft. lb. per stroke in three-quarters second with full port opening. This can be regulated to increase the time of action to any desired extent.

Exciters.—The exciters used with the generating units are of 400 kw., 125 volt, 514 r. p. m. rating and are directly connected to single overhung 600 hp. impulse water wheels. Each unit is also equipped with a 600 hp., 2,200 volt induction motor, which serves to drive the exciter in the event of any accident to the water wheel.

From the generators the energy is led through the low-tension switches to six 4,250 kva., single-phase transformers, with an additional spare unit for emergencies. When 6,600 volts are impressed on the low-tension winding, which has several taps, line voltages from 110,000 volts to 125,000 volts are obtained. All the transformers will operate in parallel under non-inductive or inductive load within their ratings. The line control at the power station is handled from the 125,000 volt switching gallery, which is equipped with oil and disconnecting switches. All station switching is controlled from a switchboard of the benchboard type designed in such a manner that the entire station with the four hydraulic units and all auxiliaries may be completely controlled both hydraulically and electrically from it.

XXXIX. A 20,000 Hp., 2,100 Ft. Head Development

The water utilized by this installation is taken from a small stream draining a plateau behind a range of mountains about 4 miles from the sea coast. This small stream has a series of rapids and falls that make it possible to obtain a head of 2,100 ft. for hydraulic purposes. To get the water to a point where it could be most advantageously used a flume made of high grade concrete 1⅛ miles long had to be built. This in itself was a very difficult piece of engineering, owing to the natural formation of the mountains. The intake is located in a wild, desolate spot in the heart of a tropical forest, and from there the flume follows the contour of the mountains, winding back and forth, crossing small streams and gullies in many places. The cross-section of this flume is 40 in. by 60 in.; it is of high grade concrete and has a finished surface inside to reduce friction.

In many places the flume had to be covered by a heavy concrete roof, owing to overhanging ledges of rock and dirt which frequently start landslides during heavy rains. Small streams which are ordinarily dry, but in the rainy season become small torrents, cross the flume at several points, and troughs had to be made to take care of this difficulty. The drop from the intake to the forebay is 30 ft.

Penstocks.—The penstock consists of five pipes of welded steel ranged in diameters from 35.4 in. at the forebay to 23.6 in. at the turbines. The average length of each section of pipe is 19.5 ft., and the sections near the power house where the pressure is the greatest (tested at 2,000 lb. per square inch pressure), and where consequently the thickness of the pipe is maximum, have a weight of 2 tons each. The penstocks at the base are embedded in a massive concrete support. Every length of the penstock is supported on concrete, and at every fifth section the pipe is embedded in a heavy concrete mass. At the angles the pipes are supported not only by concrete but by guys of steel cables, the ends of which are secured in blocks of concrete. The entire length of penstock is 6,500 ft. At the forebay and at points one-half and two-thirds of the length are placed valves which close automatically if the flow of water in the penstocks exceeds a certain speed. These valves are a protection to the power house, for, should a pipe burst near the turbines, there would be sufficient water in the penstock to destroy the station.

Power Station.—The power house is a solid building made from granite taken out of a quarry a short distance from the station. The building is located on a very marshy and shifting soil on the bank of the same river from which the water is taken. Consequently, a foundation 60 ft. deep had to be made in order to insure safety to the building and alignment of the machines. On the main floor of the station are five 3,000 kva., three-phase, 60 cycle, 2,300 volt, 514 r. p. m. generators direct-connected to impulse wheels, and three 250 kw., 220 volt compound-wound exciters, also connected to the same type of wheel.

The valve room is located under a low roof in a building adjacent to the turbines, and the piping is so arranged as to make it possible to use the water from any penstock on any turbine. All of the valves with the exception of those opening the jet on the buckets are hydraulically operated. To take care of a varying load, the turbine governors do not decrease the supply of water but deflect the jet so that a small quantity strikes the buckets on the wheel. Should the valves at the power house be suddenly closed the shock would place a tremendous strain on the penstocks and serious trouble might happen. A water cushion is provided directly under the turbine to absorb the force in the unused water when deflected from the buckets.

Table 7.—Data on Large Western Hydroelectric Systems

Name of Company	System Load-Factor (per cent)	Miles of		Plants Installed			
		High Voltage Transmission	Overhead Distribution	Hydro		Steam	
				No.	Kw	No.	Kw
Portland Railway, Light & Power Co.	47.6	277	6880	5	43,000	5	22,500
Washington Water Power Co.	65.3	631	748	3	40,000	..	..
Northwestern Electric Co.	50	65	105	1	12,000	1	7,500
Oregon Power Co.	45	92	729	1	500	..	..
British Columbia Electric Co.	45	188	66	4	65,900	..	..
West Kootenay Light & Power Co.	79	250	60	3	23,000	..	..
Western Canada Power Co.	52	55	170	1	20,000	..	..
Puget Sound Traction Co.	50	370	425	3	55,000	2	20,500
Pacific Power & Light Co.	43.0	476	777	10	13,400	5	4,900
Pacific Gas & Electric Co.	60.6	1534	3685	10	90,310	4	81,700
Mount Whitney Power & Electric Co.	56	179	1035	4	8,850	1	6,750
Great Western Power Co.	65	310	955	1	52,500	2	31,200
Western States Gas & Electric Co.	..	201	341	1	3,000	1	1,500
Pacific Light & Power Corporation	48	810	2526	8	74,300	3	..
San Joaquin Light & Power Corporation	64.0	704	1770	4	27,800	..	..
Nevada-California Power Co.	64	359	155	3	18,750	..	..
Southern Sierras Power Co.	56	274	440	2	3,480	1	5,000
Southern California Edison Co.	61.1	423	1803	6	31,600	3	57,500
Sierra & San Francisco Power Co.	31.2	480	249	3	43,375	1	18,000
Snow Mountain Water & Power Co.	58	106	..	1	6,000	..	..

The pressure of 2,300 volts from the generators is stepped up to 44,000 volts delta through 15 single-phase, 60 cycle, water-cooled, shell-type transformers connected in groups of three for three-phase operation. The power house is in the shape of a letter "T," with the transformers and high-tension bus and switchboard, etc., in the cross-bar and the generators in the leg.

Western Water Power Developments.—The Western section of the United States was first to develop its water powers to any great extent and valuable data have resulted from the early experience in the design of these plants. In Table 7 (page 145) are given the main features of the large systems that now operate water power plants in the West.

CHAPTER III

LAYOUT AND SELECTION OF PLANT EQUIPMENT

The layout and connections of electrical circuits for a generating station obviously depend on the particular conditions met. Entirely independent methods are followed in many modern developments, particularly those using high transmission voltages —60,000 volts and above. The reason for a number of the schemes used is to reduce the surges set up by high-voltage switching and the dangers to the transformers that result therefrom. In general it is desirable to reduce all the switching on the high-voltage side to the absolute minimum. While modern methods of design have reduced apparatus troubles to a minimum, it is essential to so arrange the control circuits that the troubles may be isolated and not spread to cause a shutdown of the entire system.

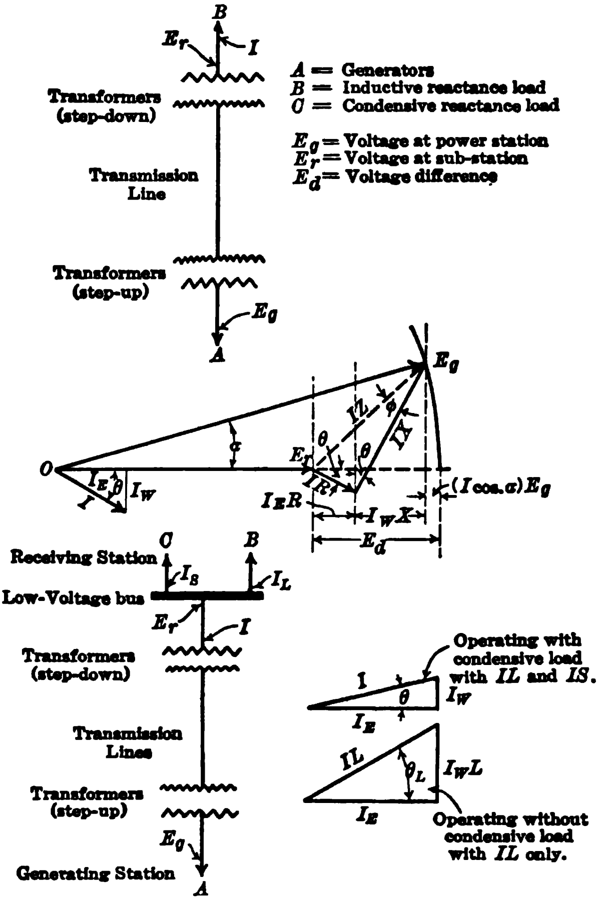


Fig. 82.—Vector Relations of Current and Voltage at Generating Station and Substations

In laying out a system of connections there are a number of general principles which must be kept clearly in mind. While reliability and continuity of service are the two main considerations, protection of the apparatus and machinery from injury should always be given careful study

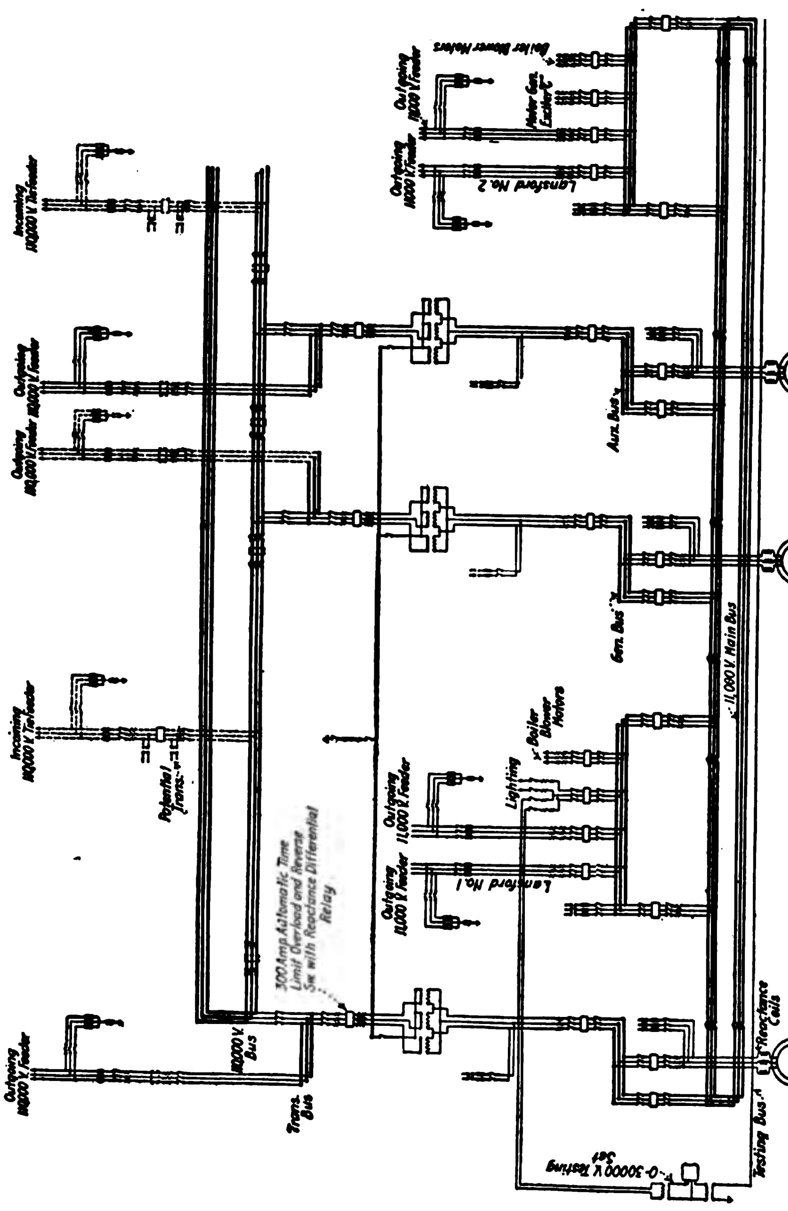

Incoming 10,000 V. Tie-feeder
Outgoing 10,000 V. Feeder
Outgoing 10,000 V. Feeder
Incoming 10,000 V. Tie-feeder
Potential Trans.
Outgoing 10,000 V. Feeder
10,000 V. Bus
Trans. Bus
300 Amp Automatic Time Limit Overload and Reverse Sw. with Reactance Differential Relay
Outgoing 11,000 V. Feeder
Outgoing 11,000 V. Feeder
Lansford No. 1
Outgoing 11,000 V. Feeder
Outgoing 11,000 V. Feeder
Lansford No. 2
Motor Gen. Exciter C
Boiler Blower Motors
Lighting
Boiler Blower Motors
Aux. Bus
Gen. Bus
11,000 V. Main Bus
Reactance Coils
2,500 Kw. Max. Rating Generator
Testing Bus
0-30000 V. Testing Set
Exciter A
Exciter B
Exciter C
Booster D
Booster E

Fig. 83.—Switch and Ring-Bus Layout of Hauto (Pa.) Station Lehigh Navigation Electric Company

It is now fully realized that the success of hydroelectric developments depends largely upon a reliable and uninterrupted service. The safeguarding of the different parts comprising the system and its connections, therefore, becomes of the greatest importance.

Generator Bus Layout.—All generators should preferably be paralleled on a common low-voltage bus, the generator switches being non-automatic. If automatic protection is desirable the switches should be provided with definite time limit relays, set very high. Reverse power relays are also occasionally installed, but are generally arranged to ring an alarm gong in case of reversal of the power, and will not trip out the switch. The various station layouts and diagrams of connections given in this text show the latest practice.

It is now fully realized that the generator bus (low-tension or low-voltage bus) should be sectionalized if the kilowatt rating of the station is very large. It is now the usual practice to limit the normal rating of each bus section to from 30,000 to 60,000 kw. It is also desirable to so sectionalize the bus that generators of sufficient rating to furnish the charging capacity of one transmission line can be entirely separated from the others and used for testing out the lines as shown in Fig. 83. A ring-bus will generally insure sufficient flexibility to accomplish this, although for a very large system a double bus is most desirable.

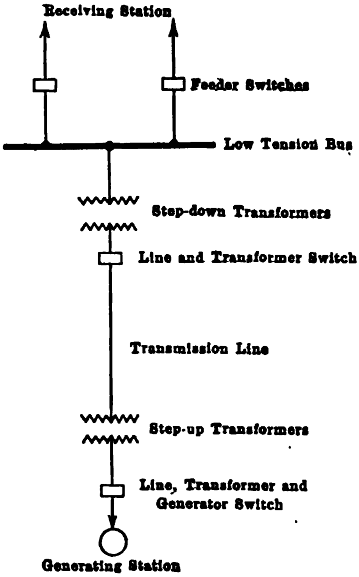


Fig. 84.—General Scheme of System Connections

In selecting oil switches their rupturing rating becomes of importance. A smaller switch can, as a rule, be used if time limit relays are employed, since this permits the initial short-circuit current rush to diminish before the switch opens. It should also be kept in mind that smaller switches can oftener be used at the substations than at the generating stations, because the reactance of the transformers and the transmission lines will reduce the short-circuit currents and their effect to a great extent.

Switching and Sectionalizing.—All the switching should preferably be done on the low-tension side of the high voltage transformers both in the generating stations and in the substations. The switches of the former should be equipped with inverse time limit relays and the latter with reverse energy relays. In the outgoing and the incoming lines, it is now customary to provide non-automatic oil switches which are used in case of sectionalizing and in addition non-automatic tie-switches are also provided between transmission lines. If more than two lines are in service it is advisable to provide high-tension transfer buses. Sectionalizing switches of the knife-switch type are usually installed at certain intervals on the towers along the transmission line, so that circuits may be divided in two or more sections to facilitate testing and for isolating line troubles, which may by this means be quickly located. With this system of connections considerable responsibility is placed on the operators, as the relays of the transformer-switches must be set at from 100 to 200 per cent. overload, and therefore above the safe continuous operation of the transformers. Take for example a system with two parallel lines connected to two transformer groups on the unit system. A trouble in one of the lines will cause it to be disconnected together with the transformers through which it is fed. This then throws all the load on the remaining line, which, with its transformers will be overloaded 100 per cent., and in order that this line should not be disconnected at this increase in the load, the relays must be set for more than 100 per cent. overload, probably 150 per cent. Transformers can, however, carry 100 per cent. overload for five to ten minutes, which should give the operator sufficient time to sectionalize the defective line and connect the transformers in parallel to feed the remaining transmission line. Practically all line conductors are so proportioned that one line or one line and a portion of another line can take care of the load to be carried, although, generally at a rather poor regulation but quite satisfactory as an emergency operating condition.

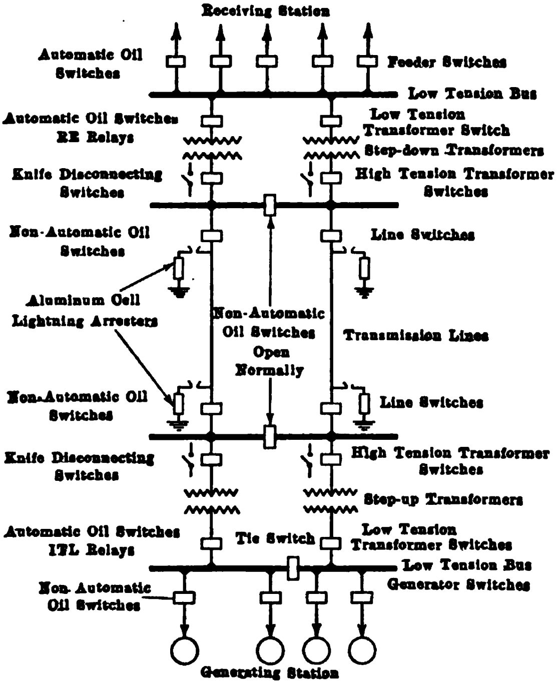

Receiving Station
Automatic Oil Switches
Feeder Switches
Low Tension Bus
Automatic Oil Switches RE Relays
Low Tension Transformer Switch
Step-down Transformers
Knife Disconnecting Switches
High Tension Transformer Switches
Non-Automatic Oil Switches
Line Switches
Aluminum Cell Lightning Arresters
Non-Automatic Oil Switches Open Normally
Transmission Lines
Non-Automatic Oil Switches
Line Switches
Knife Disconnecting Switches
High Tension Transformer Switches
Step-up Transformers
Automatic Oil Switches ITL Relays
Tie Switch
Low Tension Transformer Switches
Low Tension Bus
Generator Switches
Non-Automatic Oil Switches
Generating Station

Fig. 85.—System Connections for Paralleling High Tension Transformers on Low Tension Side. When Transformer Bank is equal in Capacity to that of Line it may be Considered a Part of the Latter

Use of Reactance Coils.—The requirements of large systems in future operation will undoubtedly be such that the automatic operation of high-tension switches will be necessary, and the present development in switches and protective apparatus promises to take care of this situation fairly satisfactorily. In order to prevent the concentration of excessive amounts of power at points of disturbances, however, generators and transformers are now being designed with high reactance and artificial reactance coils are being used in generator leads, in the bus-bars and in series with outgoing feeders.

There are certain phenomena of high frequency, but without excessive potential, which need additional means of protection. The danger to which high voltage transformers are exposed by high frequency disturbances from the transmission line is not limited to the end turns only, but danger may be done anywhere inside of the transformers, wherever a wave crest forms. This danger depends on the frequency of disturbance. A choke coil interposed between the transmission line and transformers may become a source of danger. For while it keeps line disturbances out of transformers, it may also reflect disturbances which originate in transformers back into them, and therefore increase the destruction. With high voltage apparatus connected to long distance transmission lines it now becomes necessary to provide in addition to the choke coil interposed between the line and trans-

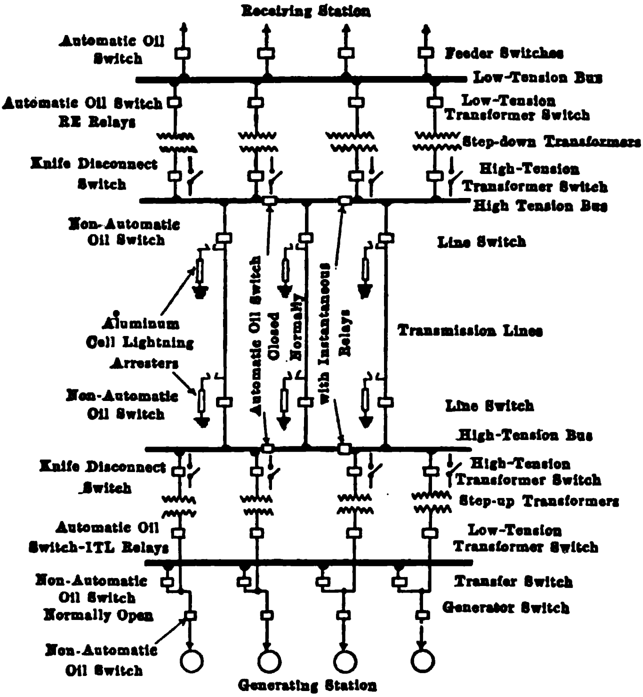


Fig. 86.—System Connections whereby Three or Four Banks of Transformers Feed Three Outgoing Lines—Transformers Paralleled on Low Tension and High Tension Sides

formers, a device which bypasses disturbances that come from transformers but does not allow line disturbances to pass into the transformers.

Grounding Generator Neutrals.—Three-phase generators should preferably have their armature windings connected in star. Operating conditions only decide whether the neutral should or should not be grounded. If grounding is done to insure selective action of feeders, it is advisable to ground the generators through a resistance, in which case the voltage strain is not limited to the star-voltage. The resistance should have a value high enough to limit the neutral current, but still low enough to insure that, if a ground occurs in one phase, it will permit a sufficiently large current to flow in the neutral to open the protective circuit-breakers. Non-inductive resistances are always preferable to reactances, since they eliminate the danger of high frequency oscillations between line and earth through the generator reactance in the path of the third harmonic, by damping the oscillation in resistance. Because of this, the grounding of the neutral of generators is of questionable value, because a ground through reactance may be dangerous owing to the possibilities of a resonance voltage rise.

Exciter System.—The rating of exciter units, the proper division of the required exciter rating into several units, the method of drive, the arrangement and connections of the different units, the proper system of automatic voltage regulation, etc., are all factors which are now given careful attention in the design of power stations for all have an important bearing upon the successful operation of the system as a whole. The rating of the exciters should be sufficient to furnish excitation to all the synchronous apparatus in the station when these machines are operating at their maximum load and at the true operating power factor. It is not enough to provide for the excitation when the alternators are operating at unity power factor, because the excitation required at lower power factors is considerably higher than at unity power factor. It will be observed from the examples of company practice and in the diagram Fig. 87, that 125 volt excitation is considered advisable for moderate sized installations, while for larger systems a 250 volt exciter system is shown to be generally used, in fact, this is the cheaper system to use.

Exciter Drive.—Exciters are usually of the direct-connected type, driven either by the main generators, by separate water wheels or by motors or by a combination of the two latter methods. The practice of installing one direct-connected exciter for each main generator has been used considerably in the past, but in modern installations it has generally given place to other systems. With a few generating units in the station, this method may be used to advantage, but in order to provide for the future it is desirable to give each exciter a rating equal to twice that required for one generator unit. For plants with a large number of main units, this system becomes rather complicated and it is furthermore open to the objection that the exciters will be affected by the speed variations of the prime movers caused by the variation in the load. Also it is void of any kind of flexibility.

The exciter system which now seems to be the most favored from the operation side is the one in which the excitation is obtained from a common source consisting of as few exciters as possible. Preference has also been given to the motor-driven exciter for the reason that on short-circuits in the system, it will drop in speed and thus minimize the effects of the short-circuit current. Furthermore, it is preferable from an operating standpoint because of the possibility of debris clogging up the small exciter turbine. If a motor-driven, water wheel exciter is used there is no need for governors on the water wheel nor a flywheel on the set because the motor acts as the speed regulator. In some of the latest hydroelectric developments a system of excitation is being used in which a small motor-driven exciter set is provided for each generator unit. The exciter has a rating corresponding to that required by its generator and the terminals are connected directly to the generator fields. The motors of the exciter sets are fed from one or two low-voltage generators driven by independent water wheels, but in addition, the connections are so arranged that if necessary the motors may be connected to the main buses through transformers, two separate sources thus being provided for driving them. With this arrangement the objection to motor-driven exciters on the ground that they are liable to fall out of

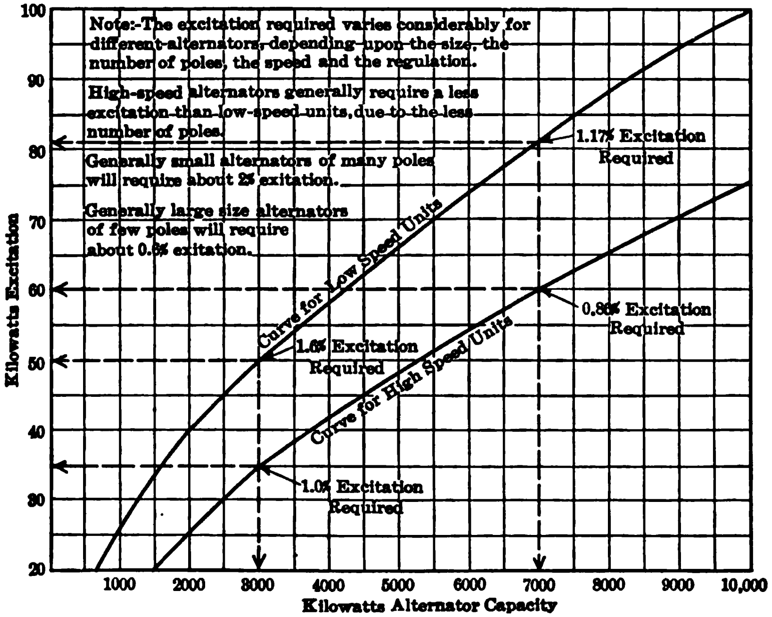


Fig. 87.—Curves Giving Approximate Exciter Capacity in Kw. for Different Alternator Ratings in Kw. and for High-Speed and Low-Speed Units

step when a short-circuit occurs on the system, is overcome because the system of excitation is entirely independent of the alternating current system. A rather late departure is in the use of storage batteries in connection with exciters. The advantage of such use is obvious, for with the failure of exciters the storage battery automatically keeps up the excitation.

Transformer Layout and Ratings.—With moderate voltage developments, it has been the general practice in the past to install one transformer group for each generator and of equal rating, even if this size was not the most economical. In general, however, with a large number of units it is more advantageous to install three-phase transformers, while in plants consisting of one or two generating units where the cost of a spare three-phase transformer is not warranted, it is preferable to install single-phase transformers. For present modern high voltage systems where it is considered undesirable to parallel the transmission lines on the high-tension side or to carry out any high-tension switching, it is the general practice to install transformers in groups, each having a rating corresponding to the line. The transformer group and the line is considered as a unit. This is commonly called the "Unit System."

The current carrying ability of transmission lines ranges from 20,000 kw. to 50,000 kw. and as the most economical size of high-voltage transformers is from 6,000 kw. to 12,500 kw., it is entirely feasible to provide one group of single-phase transformers for transmission lines up to 40,000 kw. rating, while above this it becomes necessary to provide two groups in parallel for each transmission line. The most important requirement in connection with modern transformers of large rating is, that their design must be such as to limit the current output of the system called upon to feed at times of short-circuits, and besides this to successfully withstand the tremendous mechanical strains to which the transformer windings are subjected due to short circuits. For this reason transformers are now designed with a considerably higher reactance than was formerly the case, 4 to 6 per cent. reactance now being quite common. By so limiting the abnormal flow of current into a short circuit the generating system, as a whole, is relieved from possible disastrous effects.

Power-Limiting Reactors.—The increase in size of modern generating stations and units and the concentration of enormous amounts of power in single generating stations or combined systems have made it necessary not only to increase the inherent reactance of the apparatus but also to provide artificial reactance for limiting the amount of current that may flow from any part of the system into a short circuit in apparatus or connections inside the station or close to the station. Such power-limiting reactors are divided into three classes—generator, bus-sectionalizing and feeder reactors. As a rule, the water-wheel-driven generator is designed with sufficiently high inherent reactance. Bus-sectionalizing reactors are becoming more and more used in large stations. When a bus becomes so large that for continuity of service, etc., it becomes necessary to divide it into several sections, reactors are generally placed between the sections permitting any section to draw only part of its load from the adjacent sections. Thus the short-circuit current of one section is limited to that of another section and in addition the amount drawn from any other part of the system is limited.

The scheme of reactors shown in Fig. 88 combines the advantages of the majority of other schemes in existence and possesses few of their objectionable features. The lines *D* are grouped and fed from different bus sections, *C*, which are individually energized by alternators, *A* delivering current through 5 per cent. reactors *b*. The bus sections are normally operated separately, but may be instantly connected by tie-switches *c*. To permit this emergency connection, each alternator in operation is permanently connected to a common synchronizing-bus *B* through 2 per cent. reactors which keep the alternators in step and also serve the purpose of tie-bus reactors. When this scheme is employed with a bus divided into several sections the voltage regulation is much better when there is current exchange than when ordinary bus-tie reactors are used. This is obvious from the fact that to get the same protection as here obtained 5 per cent. bus-tie reactors would have to be used and the energy exchanged between two non-adjacent sections would suffer a large voltage drop. If it is not considered necessary to protect the alternators themselves against current surges, the 5 per cent. reactors can be omitted and the operation still considerably improved over that obtained with bus-tie reactors.

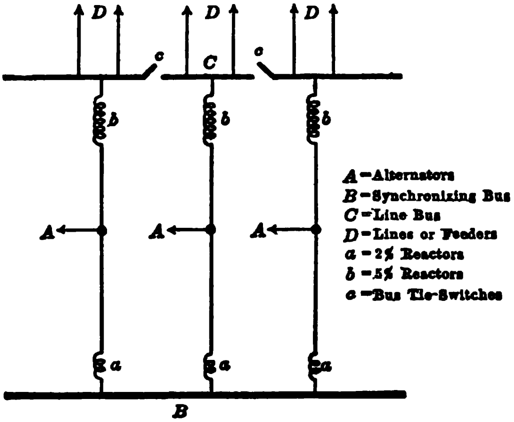


Fig. 88.—Arrangement of Reactors in Generator Circuits

Transformer Connections.—Practically all existing hydroelectric systems operating long distance high-voltage transmission lines are either delta or star connected as shown in the accompanying diagram of three-phase connections.* The voltage relations are:

(Delta) $x' = \sqrt{3}y$, or 100 per cent. of voltage between lines.

(Star) $y = x \div \sqrt{3}$, or 57.7 per cent. of full voltage between lines.

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* For general systems of connections see William T. Taylor's "Transformer Practice."

Where the power factor or Cos. $\theta = 1.0$, then

$$Cos.\,\theta = \frac{P}{\sqrt{3}EI} \text{ and } I = \frac{P}{\sqrt{3}E}$$

With power factor less than unity, then

$$P = \sqrt{3}EI\,Cos.\,\theta = \sqrt{3}EI\frac{r}{z} = 3E\frac{I}{\sqrt{3}}Cos.\,\theta$$

The number and size of the transformers and whether they should be of the single-phase or the three-phase design, depends entirely on the nature of the system and on the operating conditions. The transformers may be connected either in delta or star, isolated or grounded. The star connection with neutral grounded is generally preferable to the isolated delta-connection for high voltages.

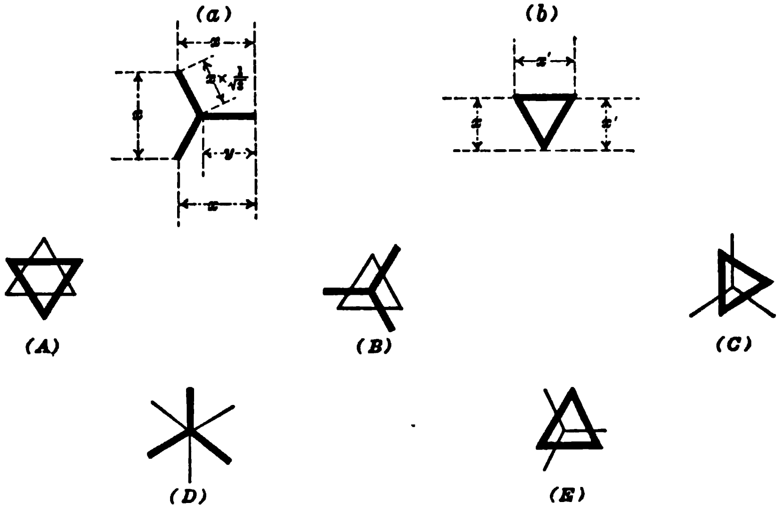


Fig. 89.—Some Three-Phase Transformer Connections

Under normal operation the voltage stress of the apparatus is the same whether the isolated delta connection or the grounded star connection be used, but in case of a ground on one line wire the isolated delta system will be exposed to a higher voltage above ground than would be the case with the grounded star system. The disadvantage of the star system is that any ground of the line wires will cause a short circuit and thus a shut-down, provided the grounded rheostat is not used. However, the delta-connected system seems to be in a far worse condition in that a ground is very often followed by a disturbance of such power that breakdowns of insulation at other points also take place. Such a disturbance of the delta system generally results in serious damage to apparatus and service. The cause of this disturbance is found in the oscillatory character of the arc which takes place from a delta-connected system to ground, together with a large amount of current which will flow in such an arc if the system is extensive. In the event of a ground on a delta-connected system, the charging current, which is a function of the voltage from wire to neutral, will be increased because the neutral is shifted from the center of the delta to one corner. This increase will be about 73 per cent. The current flowing in the arc to ground may be nearly equal to the increased charging current, which on a 60,000 volt system would amount to about 400 amperes. The grounded star-connected system is free from such disturbances, and the frequency of an arc to ground is but that of the system itself. Any danger is confined entirely to the point of failure only.

Advantages of Star over Delta Connected System.—With the star-connected system transformers are wound for only 57.7 per cent. of the voltage required in the delta system. The product of the turns times the average voltage to neutral in the star-connected group is 41.8 per cent. of that in the delta connected group. The windings have 173 per cent. of the current capacity of the windings of a delta unit. In general, the star-connected system (star on the high-voltage side) has the following advantages over the delta-connected system:

1 Subject to less insulation stresses, with or without a ground on the line.
2 The factor of safety is greater under similar conditions of operation.
3 Capable of withstanding stresses at higher frequencies.
4 A ground on the line reduces the voltage of the system with respect to the ground, but an increase in voltage with respect to the ground, occurs on all non-grounded systems.
5 Maximum potential above ground is fixed at 57.7 per cent.
6 Maximum potential above ground, less when a ground occurs on the line.
7 Less liability of disturbance on the system when switching on or off, due to a lesser amount of stored energy in the dielectric of the high voltage transformer windings.
8 Less insulation stress when switching on or off.
9 Better adapted to withstand mechanical stresses due to short-circuits, because of the higher current capacity winding with larger conductors.
10 Less number of turns of larger ampere capacity and equivalent lesser number of coils.
11 Cost of high voltage windings considerably less and much stronger.
12 With equal mechanical support, it is stronger than the delta winding for the same line voltage and capacity.
13 Under normal operation the minimum stress is equal to zero as against 29 per cent. for the delta.
14 Its average safety factor is in the ratio of 7 to 4.64 in favor of the delta-star system.
15 At a minimum cost, the distorted third harmonic and the neutral point are made stable, and with a maximum degree of stability of the neutral point—the cost being nil.
16 Third harmonic currents, and currents having a multiple of the third, cannot flow on account of being in phase with each other.
17 More direct transformation as there can be no interchange of m.m.f. between phases.

18 A considerable difference in impedance, or ratio, or both, can be employed to make up the star side of a group, without appreciably effecting the current or voltage or the division of the phases. Impossible with the delta-delta system.

19 Less number of high voltage switches are, in general, required.

20 Apparatus and transformers less costly to manufacture.

21 The high voltage side is much simpler and much cheaper.

22 In the assembly of transformers, the coils in a group must be placed in position one by one during the make-up, and the connections soldered and taped; in this operation less coils have to be handled, etc., hence, this cost of assembly is less.

23 A lightning charge will have a less effect on the windings of transformers, due to the larger and wider conductors.

24 Possible to operate and supply a three-phase load over two transmission line conductors. Impossible with the delta system.

25 The reversal of one of the transformer windings will not produce a short-circuit, but will for the delta system.

26 Advantage of not being able, under any possibility, of increasing the voltage at the receiving station as the delta-delta to star would do—the latter being $\sqrt{3}$ times higher.

Star-Star Connections.—The star-star connection of single-phase transformers is not suitable for four-wire three-phase service, nor should it be operated with the neutral grounded. The transformers would be subjected to an undue stress between layers and between coils on account of the distorted emf. between neutral and lines. In the "shell" type of transformer (single or three-phase), the third harmonic component of the waveform may be entirely eliminated by using an interconnected-star primary or secondary winding. In the three-phase "core" type transformer with interlinked magnetic circuits, the interchange of mmf. takes place between the phases, so that each phase has part of the required mmf. supplied from the other two phases during a portion of the cycle. Due to this interchange of third-harmonic mmf. there exists a third-harmonic leakage field in the air external to the coils.

Delta-Delta Connections.—The most important advantage of the delta-delta-connected group of single-phase transformers is in its flexibility should one unit fail. The stresses to which the insulation is subjected are higher than in the star-connection, and there is no means of grounding the neutral except through the intermediary of an interconnected-star group of single-phase auto-transformers. The insulation stress due to switching on and off are greater than in the star-connected system, and, with the use of three-phase units its only advantage of flexibility becomes frustrated.

Star-Delta Connections.—In star-delta-connected step-up transformers, the third-harmonic mmf. is supplied to each phase as required by the other two through the secondary delta-connected windings, so that there exists a circulating third-harmonic magnetizing current in the delta of transformers connected in this manner, which is equal in magnitude and time-phase to the equivalent component in the normal single-phase secondary

Table 8.—Present Day Use of the Star and Delta Connections for Three-phase Systems Operating at 100,000 Volts and Above.

Systems	Operating Voltage	Frequency	* Phase	Generating Station (Supply Conn'tns)
Pacific Light & Power Co.	150,000	50	1	delta-star
Au Sable Electric Co.	140,000	60	1	delta-delta
Au Sable Electric Co.	110,000	30	1	delta-star
Southern Sierras Power Co.	140,000	60	1	delta-star
Utah Power & Light Co.	130,000	60	1	delta-delta
Pacific Gas & Electric Co.	125,000	60	1	delta-star
Pacific Gas & Electric Co.	100,000	60	1	delta-star
Tennessee Power Company	120,000	60	3	delta-delta
Connecticut River Trans. Co.	120,000	60	3	delta-star
West Penn. T. & W. Power Co.	125,000	60	3	delta-delta
Inawashiro H-E Power Co.	115,000	50	1	delta-delta
Grand Rapids Muskegon Pwr. Co.	110,000	30	1	delta-delta
Ontario H-E. Commission	110,000	25	1	delta-star
Georgia Rly. & Pwr. Co.	110,000	60	1	delta-star
Alabama Power Co.	110,000	60	1	delta-star
Mississippi River Pwr. Co.	110,000	25	3	delta-star
Lehigh Navigation E. Co.	110,000	25	1	delta-star
Mexican Northern Pwr. Co.	110,000	60	1	delta-star
Cedars Rapids Mfg. & Pwr. Co.	110,000	60	1	delta-delta
Chile Exploration Company	110,000	50	3	star-star
Lanchammer, A. G.	110,000	50	3	star-star
Ebro Irrigation & P. Co., Ltd.	110,000	50	1	delta-delta
Sierra-San Francisco Pwr. Co.	104,000	60	1	delta-star
Yadkin River Power Company	103,000	60	3	delta-star
Great Falls W. Pwr. & T. Co.	102,000	60	1	delta-delta
Central Colorado Power Co.	100,000	60	1	delta-delta
Great Western Power Co.	100,000	60	3	delta-delta
Southern Power Company	100,000	60	1	delta-star
Shawinigan W. & Pwr. Co.	100,000	60	3	delta-star
Los Angeles Aqueduct	100,000	50	1	delta-star
Tata Hydro-electric Co.	100,000	50	1	delta-delta

The extensive system of the Mississippi River Power Company at Keokuk, Iowa, operates with the delta-star connections, and the highest voltage system in the world (operated by the Pacific Light & Power Company) is also a delta-star system. Both have the neutral grounded. Several other developments of 100,000 volts and above in the United States, France, South Africa, Sweden, Denmark use this system.

* This column shows single-phase units or three-phase units.

exciting current of the transformers. The effect of differences in the magnetic characteristics of transformers so connected is to cause slight dissymmetry in the delta secondary emf. waves between lines, which is due to third-harmonic components in three-phase relation which appear in these emfs. If the neutral of the star-connected primary side be connected to the generators supplying the transformers the result will be a short-circuit so far as the third-harmonic component of the generator between neutral and terminals is concerned, the flow of third-harmonic current being limited only by the impedence of the transformers, and serious heating may result to both the generator and the transformers, and, since the neutral is stable there is no necessity for connecting it to that of the generator neutral. If it is desired to ground the primary, this may be done most advantageously by grounding the neutral point of the star-connected transformers.

The three-phase "shell" type transformers do not differ materially from three single-phase transformers. The three-phase "core" type transformer with delta-star-connection has a stable neutral point and also on account of the interlinked magnetic circuits the secondary neutral to line emf. is absolutely free from third-harmonics.

Size and Number of Generating Stations.—There occurs a period in the expansion of any area served when the losses incurred in transmission and the larger expense entailed by increasing distance from the generating station make necessary the establishment of one or several additional stations to take care of the load remote from the main plant. An increase in size of station and in output eventually ceases to win economies sufficient to cover transmission losses. With hydroelectric plants producing cheap power, heavy transmission losses can be borne and still keep above the cost of locally generated power. For several years past there has been a marked tendency toward the concentration of the supply of electrical energy for all uses in a large territory from one system. The large system has economical advantages over numerous small ones. One of its most conspicuous advantages is the possibility of utilization of the diversity factor.

Practically no hydroelectric development with the rating of installed apparatus above that justifiable at minimum stream-flow is nowadays attempted without a steam-driven generating station on the system. Such a steam station may be used as an auxiliary station at periods of low water, as a reserve in case of interruptions, or as a regulating station in case of large variations in the load with the hydroelectric plant running at constant output.

As regards generating electricity by burning coal at the mine's mouth in preference to transporting it by rail to the point of consumption, each case will involve special factors of importance. Where freight is high and the grade of coal poor it may pay to use the coal at the mine, the energy then being transmitted electrically. However, where coal is of high grade and navigable transportation is available, it will undoubtedly be found cheaper to transport the actual coal. At the present time inferior fuel at coal mines is being economically used for generating electricity, its use being a favorable competitor to many hydroelectric long distance high voltage transmission systems.

Operation of Water Power Plants at Low Load Factors.—With the recent improvements in steam turbine design in large units and the increased efficiency secured thereby (water rate of 11.3 lb. per kw.-hr. for the 30,000 kw. cross-compound steam turbines of Interborough Rapid Transit Company, New York City) there has been considerable discussion among engineers of the approaching competition of the steam turbine plant with water power plants on low and medium load factors. What seems to be a careful analysis of the situation from the standpoint of water power operation was presented by Cary T. Hutchinson in *Electrical World*, August 5, 1916, and quoted in what follows:

"The discussion at Washington, D. C., on water power development (Proceedings A. I. E. E., July, 1916, pages 1131 to 1165) shows a lack of appreciation of the value of water powers for work at low load factors. This is brought out by H. G. Stott in these words: 'Now what we learn from these facts is simply this—that if we want to produce power at a lower cost than we can do to-day by hydroelectric plants, we must use some combination of steam and hydroelectric power, the steam plant for the peak loads and the hydroelectric power for that part of the load having load factors of over 60 per cent. * * * That is, if we can produce steam for the average purposes for the use of those industries which involve the use of a load factor considerably below 50 per cent, why bother with hydroelectric power at all? There is no use in going into it where the load factor is below 50 per cent. There is hardly a single hydroelectric power left which it will pay to develop if the load factor is below 50 per cent.'

"These statements are true only in case the annual cost of the hydroelectric output is a constant sum per kw. of capacity, and consequently an increasing amount per kw. hr. at low load factors. This condition obtains where power is sold at a fixed price per year, as at Niagara Falls, N. Y., which Mr. Stott apparently had in mind, but it is the reverse of true when the energy output of the plant is a constant, with equipment varied to suit the load factor.

"The controlling condition then is that the hydroelectric plant should have sufficient storage to permit the delivery of its full quota of energy at any commercial load factor, that is, with constant energy output and not constant power. In all such cases, if the costs of energy from the hydroelectric plant and from the steam plant are equal at any load factor, then the cost of energy from the hydroelectric plant will be less than that of the steam plant at lower load factors and greater than that of the steam plant at greater load factors. The writer showed this in detail in his paper before the American Institute of Electrical Engineers in 1914 (Transactions A. I. E. E., Vol. XXXIII).

"For a hydroelectric plant, let

W = total cost for the year, operation and fixed charges.

W_1 = the annual cost of that portion of the plant which does not vary with the installed capacity.

W_2 = the annual cost of that portion of the plant which does vary with the capacity.

w = the annual cost per kw. on that portion of the plant varying with the capacity; this is made up of a certain per cent. charge on an increment investment.

P = the capacity in kw.

Then

$$W = W_1 + W_2$$
$$= W_1 + wP \qquad (1)$$

"Similarly for a steam plant, let

S = the total annual cost, operation and fixed charges.

S_1 = the annual operating cost, proportional to the output.

S_2 = the annual capital charges made up of a per cent. rate on the total cost of the plant.

s = the annual capital charges per kw. of capacity.

Then

$$S = S_1 + S_2$$
$$= S_1 + sP \quad (2)$$

"The annual charge per kw. of increment of capacity (w), for a hydroelectric plant is always less than the annual charge per kw. of capacity of a steam plant for two reasons: first, the rate charged against it is less; and second, the capital sum is less. All authorities assign a less rate on investment to a hydroelectric plant than to a steam plant, fair figures are 10 per cent and 15 per cent., respectively, excluding profit in both cases. The difference in this rate is the greater depreciation and obsolescence of the steam plant and the increase in taxes due to the nature and location of the property. Moreover, the cost of increasing the installed capacity of a hydroelectric plant is less than the total cost of a steam plant, as $30 to $40 will cover the increment cost of a hydroelectric plant in nearly all cases, whereas for the steam plant the cost will be about $60 per kw.

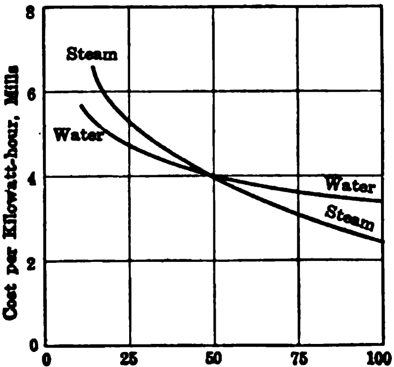


Fig. 90.—Relative Costs of Energy from a Hydraulic Plant with Storage and a Steam Plant

"Taking $40 for the hydroelectric plant and $60 for the steam plant, and rates of 10 per cent. and 15 per cent., respectively, the costs are

$$W = W_1 + 4P \quad (3)$$
$$S = S_1 + 9P \quad (4)$$

"Obviously, if $W = S$ for any particular load factor, as 50 per cent., then W is less than S for all values of P greater than that giving 50 per cent. load factor, that is, for lower load factors; and is greater than S for lower values of P, that is, for higher load factors. The disadvantage of the steam plant at low load factor is made greater by the increase in the operating cost S_1; that is, both terms of equation (4) increase at low load factors.

"These facts are brought out in Fig. 90, in which the costs are shown to be equal at a 50 per cent. load factor. The curve for the hydroelectric plant falls below that for the steam plant at a lower load factor, and rises above that for the steam plant at a higher load factor. The precise figures used may vary widely without affecting the general statement that water power plants with storage are relatively cheaper at low than at high load factors.

"These facts can be illustrated by a specific case for which detailed costs are available. Table 9 gives the costs to build a large water power plant, including transmission lines and substations equipped for different load factors. The plant having adequate storage to secure the delivery of the same quantity of energy under all load factors.

TABLE 9—CONSTRUCTION COST OF WATER POWER PLANT INCLUDING LINES AND SUB-STATIONS

Load Factor Per Cent.	Cost to Build Per Kw. Dollars.	Cost to Build Per Kw. Hr. Cents.	Annual Cost Per Kw. Hr. Mills.
25	80	3.65	4.05
50	120	2.75	3.15
100	200	2.28	2.68

"The cost of energy increases materially at low load factor, but even so is lower than for the steam plant, for which the 15 per cent. on a cost of $60 at 25 per cent. load factor is itself equal to 4.15 mills, greater than the total cost of the water power, without considering the operating costs. This all means that for such water powers the peak should be carried by the water and the base by the steam, each being then used to the greatest advantage.

"One other point is conspicuous by its absence in nearly all comparisons of the cost of water and steam power, and that is the ignoring of the heavy obsolescence of steam plants. The history of steam plants in New York illustrates the point well enough. The average life of these plants has been less than ten years, the average output probably less than 2500 kw. hr. per kw. of capacity, which means a total output of 25,000 kw. hr. per kw. during the useful life. The cost has averaged more that $100 per kw., so here is an obsolescence charge of 4 mills per kw. hr., which is usually blinked at. The immediate saving in coal looms large while the deferred cost of obsolescence vanishes in the distance. All improvements and increased economies in steam generation mean increase in the obsolescence cost and the possible introduction of oil engines threatens greater burdens.

"The stability of water powers has not been sufficiently emphasized in these discussions. The water power with storage is becoming important, and as the conservation movement leads to this water powers operated at low load factors will increase."

The efficiency of any hydroelectric plant depends largely on operating conditions, and the efficiency and reliability of an operating staff. Modern developments now place more weight on this matter than on any other in a hydroelectric system. The value of plant efficiency is generally recognized and maintained at the most efficient point when possible. It simply means maintaining the best conditions of operation for different kilowatt hour outputs at the lowest possible cost.

High-tension Plant Construction.—There have been certain changes in the design and construction of hydroelectric plant equipment that have improved the construction and operation of high tension stations and added to their reliability. Among these are modifications in transformer and switch practice. Of late years the three-phase unit has become popular, a development that really belongs to the early history of transmission as worked out in Germany. American engineers for a long time were very cautious in adopting them, since it seemed wiser to use separate transformers for each phase so that the plant might be worked on an emergency connection in case a single transformer failed. The introduction of improved lightning arresters, particularly the electrolytic type, have in considerable measure removed the danger of burn-outs and encouraged the use of highly efficient and economical three-phase transformer units. Whether these or the separate transformers are chosen, however, depends somewhat on the size of the plant and the character of service. A sufficiently large installation can very well carry one or more three-phase units in reserve while a small plant might still find it advisable and economical to employ separate transformers.

Switching apparatus is a frequent source of trouble in station operation, and not only is it desirable to select comparatively simple and easily-operated devices, but to put them where the connections, including disconnecting switches, are conveniently installed and easily inspected.

A great deal of information which reflects modern practice in these matters was given in an article of the *Electrical World,* November 18, 1916, entitled "Construction and Layout of High-Tension Equipment," by M. M. Samuels and the suggestions under the following headings have been abstracted therefrom. The practice outlined and the construction shown by the illustrations are those which has been employed by the J. G. White Engineering Corporation in various plants.

Indoor and Outdoor Transformers.—Transformers are now being built for very high voltages and ratings for both single and three-phase circuits. Indoor-type transformer tanks are built mostly of corrugated steel and are mounted on cast-iron bases. Steel bases are being used more extensively than they formerly were, however, on account of the fact that modern welding methods permit attaching them to tanks very easily. Since indoor transformers of large rating are always water cooled no special radiators are required, the tank surface in addition to conversion currents in the water being sufficient to carry away the heat energy.

For outdoor transformers, however, water cooling is not always practical, since units are often located where water is either not available at all or where it can be obtained only at considerable cost. Even when cooling water is obtainable at outdoor stations it is sometimes inadvisable to install water-cooled transformers, since there are usually no attendants to see that the circulation of cooling water is maintained and the transformers thus prevented from overheating. If water-cooled transformers were used under such conditions it would be necessary to have the oil switch trip coil actuated by the temperature measuring apparatus or by the discontinuance of water circulation. This cannot be considered as a very reliable method, nor could it be considered desirable even if it were reliable. These service limitations have brought about the radiator-type of self-cooled transformer, which has several radiator-shaped cooling surfaces attached to the tank.

In hydroelectric power houses where a great quantity of water is available at little cost, the cooling water is usually taken from the intake, circulated through the transformers under the force of gravity and discharged into the tailrace, so that no elaborate water piping is required. At substations, however, where city water often has to be used, or where the water has to be pumped at great expense, a saving usually can be realized by installing cooling facilities and recirculating the water through the transformer. Cooling towers have been used to great advantage for this purpose, but recently cooling ponds with spray nozzles are being preferred by most engineers. In steam stations, it is sometimes an advantage to pass the transformer water through the water heaters, thus utilizing part of the energy lost through radiation from the transformers. The arrangement of piping and space required for this as well as the oil filtering and pumping equipment should be given special consideration when making a preliminary power station or substation layout since the crowding of piping will often cause complications in the high-tension wiring, which should by all means be avoided.

Mounting of Oil Switches.—Next in importance to the transformer as regards rapid development of construction is the oil switch. There is a new type of switch in practically every new station that is constructed. Low-tension oil switches differ so much that different bus structures have to be used with nearly every type. On the other hand, all modern high-tension oil switches have approximately the same outside appearance, and there is very little difference in the required floor space. Older types of high-tension oil switches required concrete or steel foundations in order to raise the terminals above reach. Most recent oil switches, however, are arranged for pipe or angle-iron mounting, which not only does away with the necessity of a foundation, but permits the tank being lowered easily for repairs or examination. For automatic operation of the older types of high-tension oil switches, series relays were mounted on high-tension insulators and connected with small auxiliary tripping switches by means of long wooden rods. This rather clumsy and primitive construction is now very seldom used, however, its place having been taken by current transformers. Where the line current has to be measured, as is required in most cases, the meter current transformers are utilized for operating the relays. When metering is not required, bushing-type transformers mounted on the oil-switch terminals are generally employed for operating the relays.

Since a continuous wall or steel member is seldom installed along a line of oil switches on which to support a control bus, individual circuits usually have to be carried directly from the switchboard to each oil switch. A method of supporting high-tension oil switches so their terminals will be above reach, which does not require elevated foundations, is to mount them on an angle-iron framework and equip them with a manually operable mechanism for lowering the oil tanks. In using this arrangement, hangers carrying pulleys are attached to the frame, the hoisting cable laid in the pulley grooves and looped under the pulleys on each end of the tank, and the tank detached from the frame and lowered. Pipe supports may also be employed for mounting oil switches.

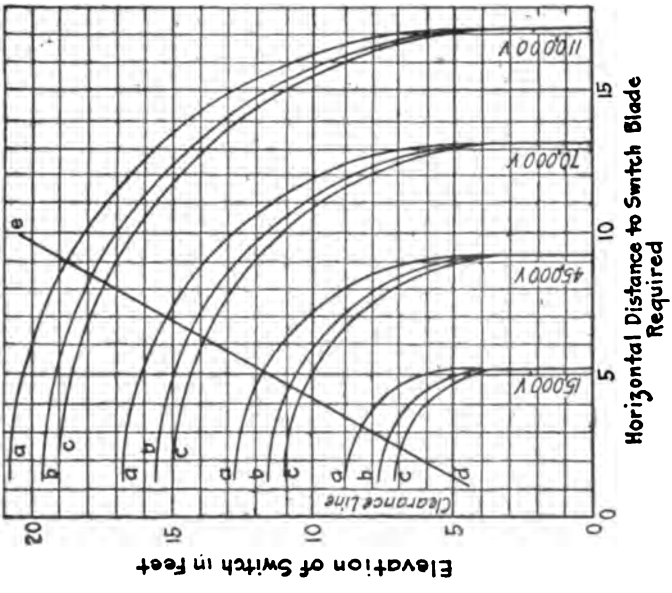


Fig. 91.—Space Required for Operating Disconnecting Switches at Various Elevations

In plotting the curves it was assumed that the operators are of average height, curves a, b and c representing requirements with high, medium and low-reach switch sticks. Line d-e indicates the maximum inclination of the switch stick from vertical when closing a switch. It may be assumed that operators can stand 30 deg. to either side of a 300-amp. switch.

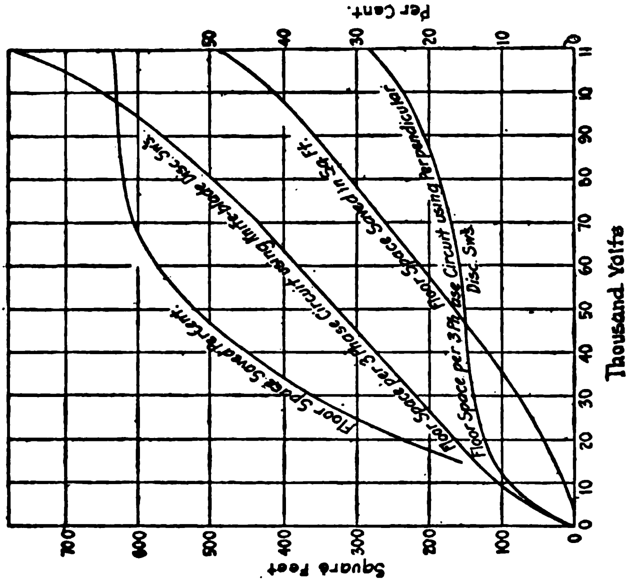


Fig. 92.—Switching Floor Space Required per 3-Phase Circuit

In plotting these curves it was assumed that knife-blade perpendicular disconnecting switches are used on both sides of each oil switch. The floor space given includes that for switches and aisles. The type of perpendicular disconnecting switch installation referred to is shown in Fig. 94.

Disconnecting Switches.—Except in extreme cases, such as for bus selection, disconnecting switches are auxiliaries to oil switches, serving only to isolate the switch when inspection or repairs are necessary. On this account, they may be considered a necessary evil and should not be permitted to have too much influence upon the character and quality of a high-tension layout. All of the old-type disconnecting switches with the exception of the pneumatically operated units, were usually opened and closed by means of a switch hook attached to a hickory stick of suitable length. This method requires an operating aisle which increases in width with the voltage as shown in the curves of Fig. 91. The space cannot be utilized for any other purpose and is thus wasted. Especially in hydroelectric stations

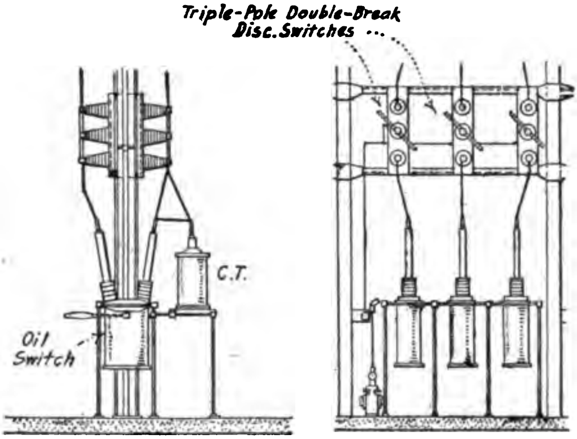


Fig. 93.—Triple-pole Double-break Disconnecting Switch and Oil Switch Mounted on Pipe Supports

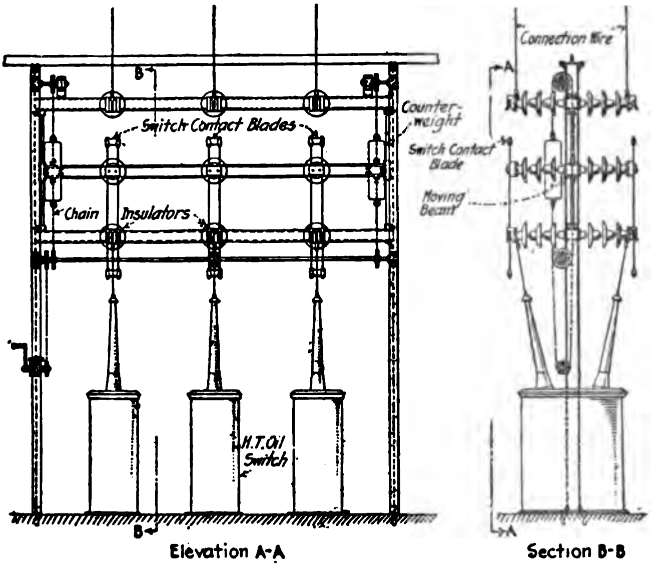


Fig. 94.—Bayonet-type Disconnecting Switch Requiring Small Aisle Space

with elaborate substructures, this has called for an enormous expense and has led to the development of many types of disconnecting switches which are operated from the floor by means of a pipe mechanism. Most of these switches are of the pivot type, the center insulator turning around its pin as an axis and contacts being made at the top as well as at the bottom. Such switches were installed by the J. G. White Engineering Corporation in the Frackville substation of the Eastern Pennsylvania Railways' Company. They are rated at 30,000 volts. Six disconnecting switches, three on each side of each oil switch, are operated by one common lever, as shown in Fig. 93. Such switches permit a considerable saving in the width of the operating aisle, but require more space between the individual switches, since the blades rotate in the same plane.

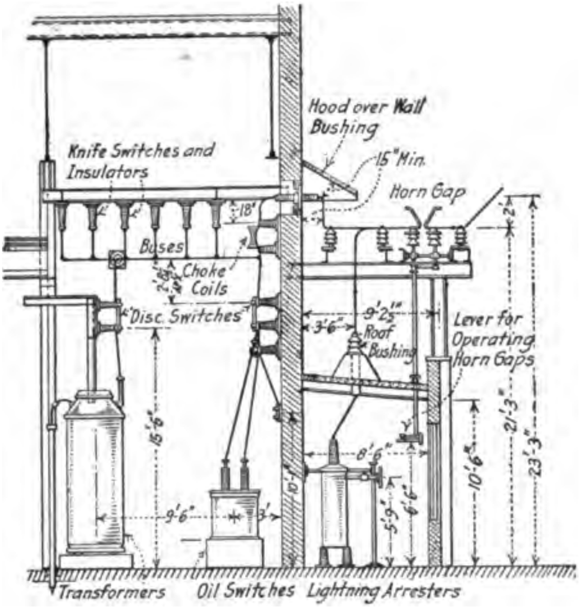
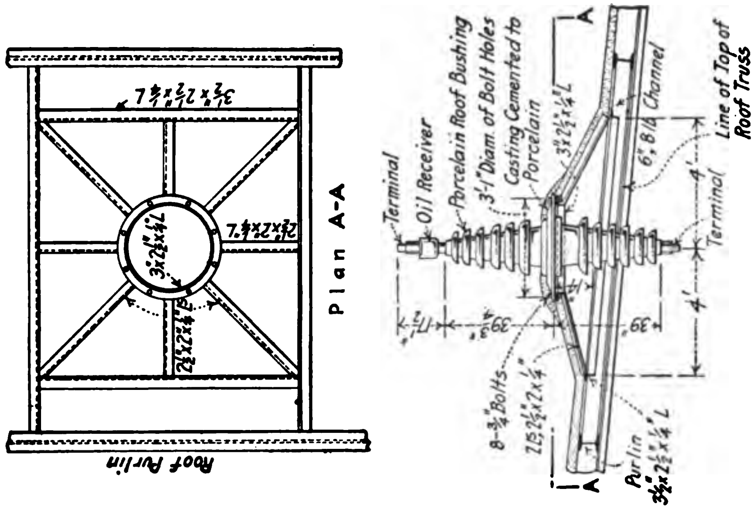


Fig. 95.—Conditions Under which Both Wall and Roof Bushings were Required

A very good type of disconnecting switch is shown in Fig. 94. This switch was designed by The J. G. White Engineering Corporation and is now employed at the Parr Shoals plant in South Carolina and Stevens Creek plant at Augusta, Ga., in both power houses and substations. The enormous amount of floor space saved by its use is shown in the curves of Fig. 92. In this case also, six disconnecting switches are operated simultaneously, thus saving a great deal of time which may be of great importance when it is necessary quickly to examine an oil switch. While a chain mechanism is employed for operating the switches it should not be difficult to design a bell-crank arrangement if this should prove to be of any advantage.

Air-Break Outdoor Switches.—For small outdoor substations connected to transmission lines and serving industrial loads, the air-break pole-top switch is being successfully used. The most practical designs operate on the principle of breaking the load first through regular switch jaws and then breaking the arc by means of horns, a toggle or other operating mechanism being provided to insure uniform switch opening. Circuits carrying loads as large as 20,000 kw. have been opened successfully by means of these switches but on account of the possibility of surges being set up such switching is advisable only in emergency cases. In Chapter 7 results of tests on air-break switches under different conditions are given. Whenever the expenditure for oil switches is at all warranted they should be installed.



Cross-Section

Fig. 97.—Suitable Method of Mounting 120,000 Volt Roof Bushing

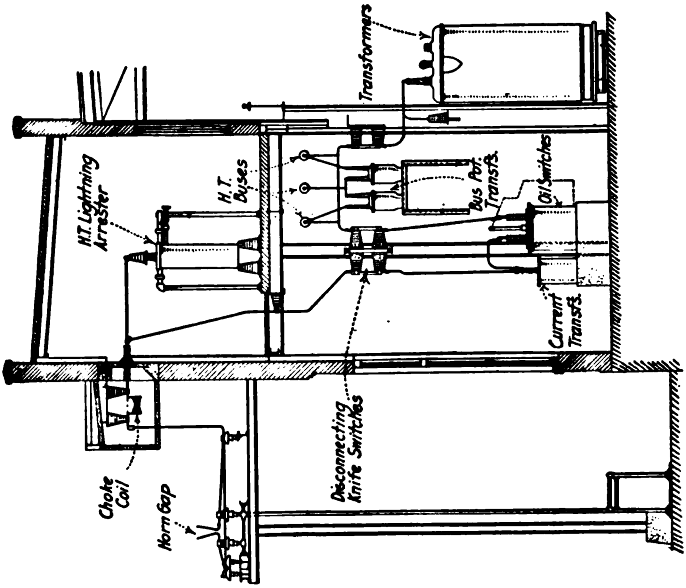


Fig. 98.—Method of Extending 35,000 Volt Conductor through Wall

Wall and Roof Bushings.—The problem of bringing a high-tension wire out of a building is similar to bringing one out of a transformer. For the same reason that most transformer high-tension leads are brought out through the top it will be found best to bring high-tension conductors out of power houses or substations through the roof. In some cases, however, it will be found better to use wall outlets. No fixed rule can be made in this respect, since the method depends on the particular layout, the arrangement of buses, disconnecting switches and lightning arresters being the ruling factor. For pressures of 100,000 volts and higher, the weight of the outlet bushing and its great size as well as the required ground clearance from steel must be taken into consideration when designing the roof. A good example of a 120,000 volt roof outlet cone is shown in Figs. 97. The base casting of the porcelain bushing is bolted to a circularly-bent angle

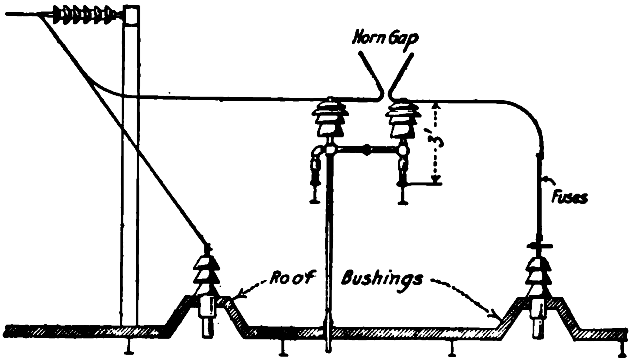


Fig. 98.—Roof Installation of Horn Gaps Operated from within Station and Connected Therewith through Roof Bushings

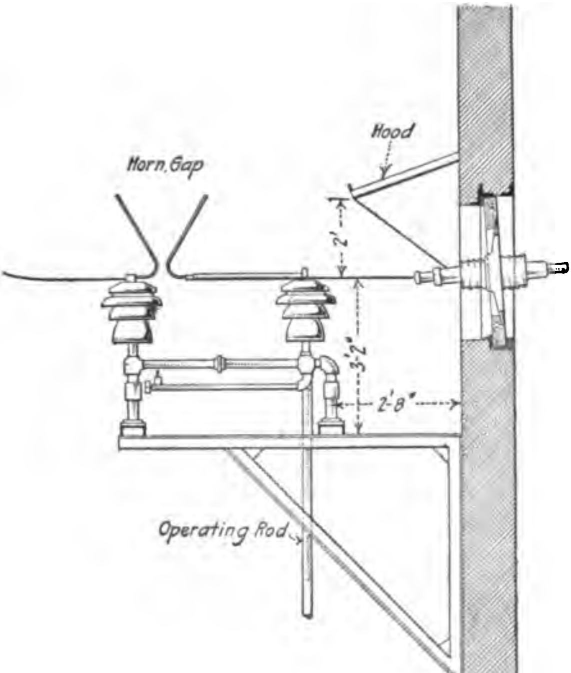


Fig. 99.—Wall-type Bushing for 60,000 Volt Installation

iron which is attached to the roof purlins by radial angle irons. This construction was used in the Ocoee River power house of the Tennessee Power Company. In Fig. 98 is shown the type of roof outlet used in the Stevens Creek (Ga.) power house, and also a roof installation of horn gaps with the operating rod running through the roof slab. It may be pointed out that the roof beams are spaced with due regard to electrical conditions.

Both roof and wall outlets are shown in Fig. 95 with the horn gaps mounted on special steel work over the lightning-arrester leanto. This arrangement is used in the 35,000 volt part of the Rock River power house of the Tri-City Railway & Light Company, Davenport, Iowa, and shows what careful planning can accomplish under the most unfavorable conditions in an old building. Different types of wall outlets are shown in Figs. 96 and 99. The former is a 35,000 volt gashouse substation connected with the Tri-City Company and the second is a 60,000 volt arrangement at the Parr Shoals (S. C.) power house. The method of setting wall bushings must depend in each case on the particular conditions at hand, and due consideration must be given to architectural features.

General Arrangement and Wiring.—No rules or classifications are possible with reference to high-tension wiring. However, given certain types of apparatus and a wiring scheme it will generally be easier for a designer to devise a good arrangement with high-tension equipment than it will be to work a low-tension bus structure into crowded space. Simplicity, directness and accessibility of all conductors should be the underlying principles of all high-tension designs. While loose wiring or strain-insulator units may be suitable on transmission-line towers they are out of place in any station. Only rigid conductors, well supported and properly spaced, should be considered for high-tension station layouts. For this purpose copper pipe or brass pipe is preferable to wire. Table 49 (page 296) gives all the necessary data for pipe conductor installations.

Clearances for Station Wiring and Apparatus.—Minimum and preferable clearances are given in Table 10. In this connection it may be pointed out that all energized parts should be out of reach to prevent accidental contact. The buses may be arranged either in a horizontal or a vertical plane, it being safe to disregard the arguments advanced that something may accidentally fall across horizontally arranged buses and short circuit them, and that an operator holding a length of pipe may short-circuit vertically arranged buses. There is no more chance of a piece of metal falling across horizontal buses than there is of a piece of pipe short circuiting vertical buses. Choke coils should be located as near the building entrance as practicable and if possible even outdoors, as shown in Fig. 96.

Power Station Lighting.—In most cases too little attention is paid to the installation of lighting units and the selection of proper fixtures in the construction and design of power stations. The tendency in working out

TABLE 10.—CLEARANCES FOR CIRCUITS AND APPARATUS AT DIFFERENT VOLTAGES*

MAXIMUM VOLTAGE	SPACING OF LIVE PARTS, IN.				SPACING OF BUSES, IN.				LIVE PARTS TO GROUND, IN.				MIN. SPACING OF HORN GAPS, IN.	MINIMUM HEIGHT OF LINE OVER HORN GAP, IN.	FLOOR SPACE REQUIRED FOR 3-PHASE LIGHTNING ARRESTER, FT.	FLOOR SPACE REQUIRED FOR 3-PHASE OIL SWITCH, IN.		LENGTH OF STICK FOR OPERATING KNIFE BLADE DISC SWITCHES, FT.	MINIMUM ELEVATION OF KNIFE BLADE SW'S, FT.	MINIMUM WIDTH OF OPERATING AISLE FOR KNIFE BLADE, SW'S, FT.
	Indoor		Outdoor		Indoor		Outdoor		Indoor		Outdoor					Indoor	Outdoor			
	Minimum	Recommended	Minimum	Recommended	Minimum	Recommended	Minimum	Recommended	Minimum	Recommended	Minimum	Recommended								
2,300	2½	4	6	8	6	8	8	12	2	3	4	6	..	..	..	..	..	..	..	..
7,500	4	4½	12	15	9	10	15	18	3	4	5	7	..	..	..	..	..	..	..	..
15,000	5	6½	18	21	10	12	20	24	3½	5	6	8	48	60	5x 9	..	..	4	7	5½
22,000	7½	9	27	30	12	15	36	39	6	7½	8	10	52	72	5x 9	26x 82	..	5	8	6½
35,000	12	15	33	36	18	22	38	41	10	12	11	14	60	84	5x11	34x 86	..	6	10	8
45,000	16	19	42	46	24	27	50	54	14	16	14	17	74	96	9x14	40x100	40x124	8	11	9½
70,000	24	30	60	66	36	42	72	78	21	24	23	26	98	120	11x17	48x124	48x142	12	15	13½
90,000	32	38	72	80	48	54	88	96	27	32	29	34	120	132	13x22	60x142	60x146	14	17	15
110,000	38	48	80	90	60	66	100	110	33	38	40	45	120	144	13x25	70x180	70x184	16	19	17½
140,000	50	60	100	120	72	84	132	144	42	50	45	54	140	180	..	..	..	..	..	..

* Clearances refer to bare conductors. Areas do not include passageways. Areas for lightning arresters and oil switches are for estimating purposes. There are switches on the market requiring less space. Areas for lightning arresters include horn gaps over tanks and are for fused arresters. For non-fused arresters considerably less space is required. Spaces not filled out represent apparatus on which the different manufacturers vary too much to permit obtaining an average or maximum.

station lighting systems is largely the same as in other illumination problems, namely, to approach daylight; to use general instead of individual illumination wherever possible and to place fixtures out of the line of vision when possible. With modern high-wattage, gas-filled lamps, overhead illumination is possible in most cases. Usually powerhouses have a crane and fixtures can be placed high between or below the roof trusses so that they can be reached from the crane. With a proper selection of reflectors, a nearly uniform distribution can be secured in practically all cases without difficulty.

The recommendation of the N. E. L. A. of 2.5 foot-candles intensity for power houses can be considered as ample. However, it must not be forgotten that reflectors and lamps will be covered with dust and that the attendant will not always have or take time to keep them clean. From 15 per cent. to 25 per cent. should, therefore, be allowed to account for this probable reduction in the efficiency of the lighting unit. In order to illustrate the use of overhead lighting, a typical power-house building is shown with a suitable arrangement of lamps and fixtures which may be considered good practice under average conditions.*

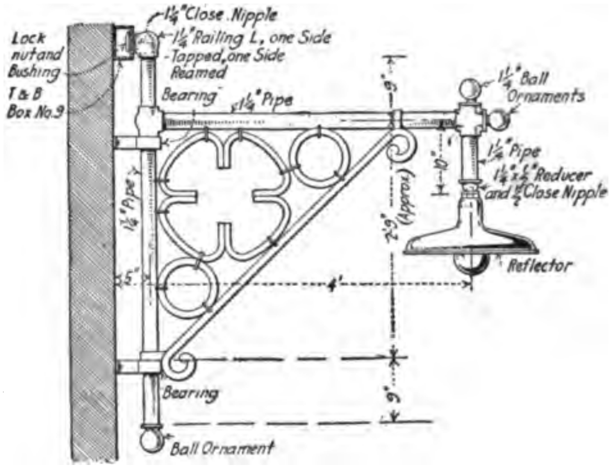


Fig. 100.—Large Bracket Fixture for Wall Mounting Arranged to Permit Turning Out of Way of Crane

Bracket Fixtures.—In some cases it will be impossible to do away with bracket fixtures altogether. When large bracket fixtures are required, they should be so arranged that they can be turned out of the way to permit a crane to pass. Such a fixture is shown in Fig. 100, in which all wiring is inclosed. Smaller bracket fixtures can be made up of standard pipe fittings, as shown in Fig. 101. These fixtures can be easily made up on the job, and are substantial, make a strong and pleasing appearance and are more suitable for power-house use than are flimsy goosenecks or similar fixtures. The same method can be adapted for fixtures out of doors.

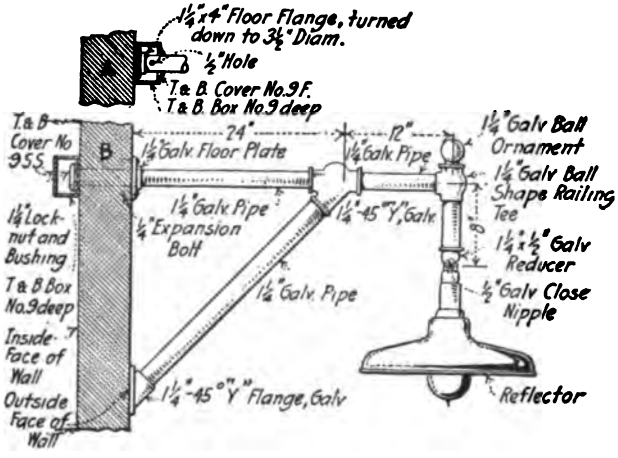


Fig. 101.—Large Fixture for Outdoor Mounting Over Power Station Entrance

This fixture is made up of standard 1¼-in. pipe fittings and can be made to extend ta considerable distance from the wall. *A* shows mounting of same fixture indoors. A 1¼-in. standard pipe flange can be turned down to fit inside a 4-in. round box.

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* Installation of Lighting Units in Power Houses, by M. M. Samuels, *Electrical World*, May 13, 1916.

Switchboard Lighting.—Both the front and back of a switchboard should be well illuminated. In most cases the general illumination will take care of this and no special lighting will be required. Whenever special switchboard lighting must be installed, a trough reflector held at a proper distance from the switchboard should be used with either Johns Manville "Linolite" lighting units and reflectors or standard 10-watt tungsten units with suitable reflectors. An easy method of supporting the shade without giving it a clumsy appearance is shown in Fig. 103a. The switchboard pipe supports are extended up and the shade is bracket supported therefrom. A small hole in one of the pipes will let the wires pass into the shade. In general the problem of switchboard illumination is about the same as that of lighting paintings in art galleries, with the only difference that a painting requires the same amount of light over its whole height, while a switchboard requires more light at its upper part where the instruments are mounted.

The rear of the switchboard will be best illuminated by small brackets on the back wall, or by small overhead fixtures suspended from the tie rods. Frosted lamps will be found more satisfactory in the back of the switchboard as it is installed in the average power station than clear lamps.

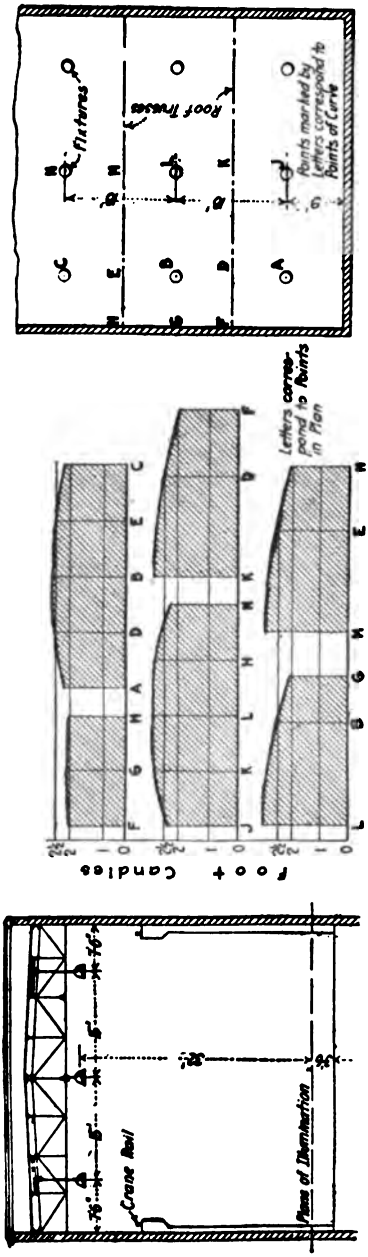

Fixtures
Roof Trusses
Points marked by Letters correspond to Points of Curve
Letters correspond to Points in Plan
Foot Candles
Crane Rail
Plane of Illumination

Fig. 102.—Typical Station Lighting Layout with Lamps Mounted Overhead and Providing Uniform Distribution of Light on a Plane 3.6 Ft. above Floor Line. Distribution Based on Standard Curve for 200-Watt Gas-filled Tungsten Lamp in Metal Reflector 8.25 in. in Diameter. The Center Fixture is Mounted on Cross-Bracing between Trusses and Side Fixtures Suspended from Roof Purlins

Whenever an emergency source, such as a control battery, is available, a small lever switch equipped with a low-voltage relay, which will turn on an emergency circuit automatically in case the main source of light should fail, should be installed on the switchboard. Such an emergency circuit can be extended over the entire power house. In most power houses the whole lighting system can be thrown on the exciter bus, and in this case it will be necessary only to install emergency lamps near the switchboard, so that the operator can see to shift the double-throw switch over to the exciter bus.

Storage Battery Room and Gage Fixtures.—Overhead fixtures are recommended for storage-battery rooms. They should be substantial in construction and vaporproof. Such a fixture is shown in Fig. 103b made up of V. V. fittings No. 52,188 or No. 52,198 or Benjamin fittings No. 630 or No. 1,568 the latter being preferable for a 200-watt lamp. Any other substantial vaporproof fixture will, however, be satisfactory.

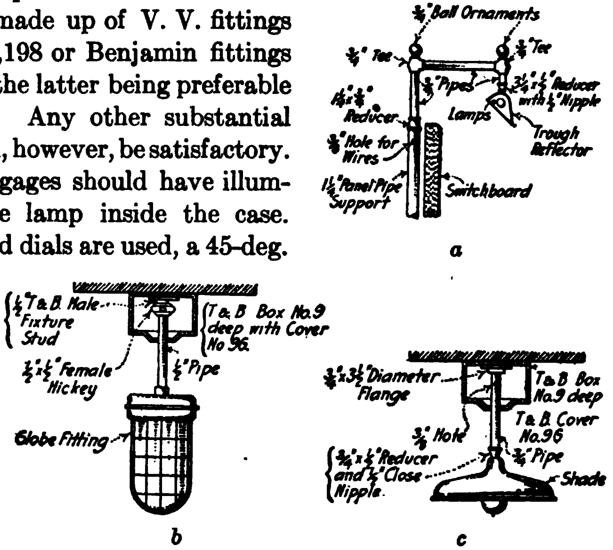


Fig. 103.—(*a*) Method of Mounting Trough Reflectors for Switchboards on Panel Pipe Supports. (*b*) Fixture Adapted for Storage Battery Room Use. (*c*) Method of Suspending Heavy Reflectors.

Wherever possible gages should have illuminated dials, with the lamp inside the case. Where non-illuminated dials are used, a 45-deg. shade above the gage should be installed for each gage. No rules can be given for the horizontal and vertical distance of the lamp from the gage. This depends on the height of the gage over the floor and also on other sources of light in the neighborhood. For vertical tubular gages, such as water or vacuum instruments, a tubular lamp preferably frosted, with a suitable longitudinal shade placed at one side of the gage will usually give best results.

Switches and Circuit Wiring.—All switch cabinets should be made of heavy iron and have double-pole lever switches for all circuits. Switch handles should be of the spade type with a button on the front. It should be remembered that these switches will be operated by men accustomed to handling heavy machinery and for this reason snap switches should not be used in power stations. Push button switches mounted in heavy iron boxes should be adopted instead. Separate circuits should be run for the attachment of receptacles so that it should not be necessary to turn on all the lights when a portable unit is to be used. At least one receptacle should be provided at each machine and at every place where close inspection may at times become necessary. For portable lights deck cable should be used and sockets and receptacles of strong design installed.

Since fixture wire should not be used for lamps rated at 200 watts and above, slow-burning wire is recommended run inside the fixture stems. A switch should be provided for each large fixture at a suitable place, so that lighting units may be turned off when a particular part of the station is not in use.

High Tension Room Lighting.—Lighting of high-tension rooms is a difficult problem. Uniform illumination is out of the question, since the lighting units must be placed in accessible positions and therefore must generally be very low. Furthermore, it is difficult to illuminate disconnecting switches and buses located at high elevations. Flood-lighting may be suggested as a possible solution of the problem of properly lighting high-tension rooms. Otherwise it is necessary to resort to special reflectors and frosted lamps. Guards should in most cases be provided for incandescent lamps to protect the filaments from static effects. When lightning arresters are mounted on the roof, fixtures can easily be attached to the pipe framework of the arrester. A switch should be placed indoors near the ladder or stairs leading to the roof. A pilot lamp can be provided near this switch to tell the operator when the lights on the roof are on.

Equipment and Operation of a Typical System.—A concrete example of a moderate size and moderate head hydroelectric development using storage will serve to illustrate the losses of the entire plant from the intake of pipe lines to the distant receiving station, and also the effect of proper operation of the system. The system here referred to has a storage to take care of low-water periods, hence efficiency means more than a plant without any storage features. The physical data for this plant are as follows:

Pipe Lines and Penstocks.—Two 15,865 ft. wooden stave pipe lines; one of 68 in. inside diameter, dividing at a point 950 ft. from the power-house into two 48 in. inside diameter riveted-steel penstocks, and one of 49 in. inside diameter, dividing at a point 1,000 ft. from the power-house into a 48 in. inside diameter riveted-steel penstock. The entry of the pipe is bell-mouthed. The pipe lines have a slope of 4 ft. per 1000 ft. to give a velocity of 10 ft. per second. The pipe line contains five steel elbows, where the curvature is greater than 20 deg. These elbows are made to a 15 ft. radius and have angles respectively 92, 55, 60, 65, and 45 degrees. The total head is 605 ft.

Water Wheels and Turbines.—Two 8,000 hp. Francis turbines operating at 600 r. p. m., and two 2,400 hp. Pelton water wheels (impulse) operating at 400 r. p. m. The wheels are equipped with two runners, each of which is supplied from a needle and a deflecting nozzle.

Generators and Exciters.—Two direct-connected, three-phase, 60 cycle, 2,300 volts, 4,000 kw. revolving-field units, and two three-phase, 60 cycle, 2,300 volts, 1,200 kw. revolving-field units. One 150 kw. water-wheel driven exciter and two 75 kw. water-wheel driven exciters, 125 volts.

Step-up Transformers (in power station).—Nine single-phase units, each of 1,500 kw. capacity, stepping-up the voltage from 2,300 volts to 60,000 volts three-phase, star-connection, with neutral point of system grounded.

Transmission Lines.—Two three-phase lines, each 39 miles long. One line is of 0.258 in. diameter, solid medium hard-drawn copper conductor; with wires spaced on 6 ft. triangle. One line is of 0.46 in. diameter, seven-strand hard-drawn copper conductor, the wires being placed in a 7 ft. triangle.

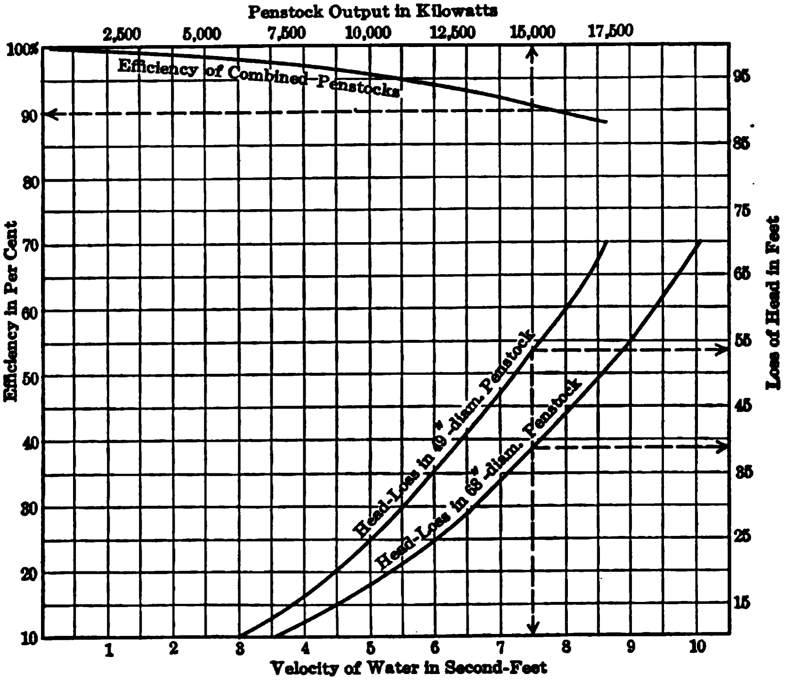


Fig. 104.—Complete Penstock Efficiency in Per Cent. and Total Loss of Head in Each Pipe Line for Different Velocities in Second-Feet

Step-down Transformers (in receiving station).—Eight single-phase units, each of 1,500 kw. rating and made with a ratio of 54,000 volts, three-phase, to 15,000 volts and 2,500 volts, two-phase, making four groups of transformers of two per group. The low-voltage coils are connected in series for 15,000 volts and in multiple for 2,500 volts.

This plant has been in successful operation for some time past, and the analysis of the complete hydroelectric plant losses given here may be considered close to average values. The curves shown in Fig. 104 give the efficiencies of the combined penstocks and the friction-head at varying velocities in second ft. The loss in these penstocks was computed from records taken by recording gages at the power house. The results so obtained were afterwards checked by computing the loss from the efficiency shown under each test, and agreed very closely with the records taken. Losses in the water wheels and generators were computed from half-hour wattmeter readings on the generators as recorded in the power station.

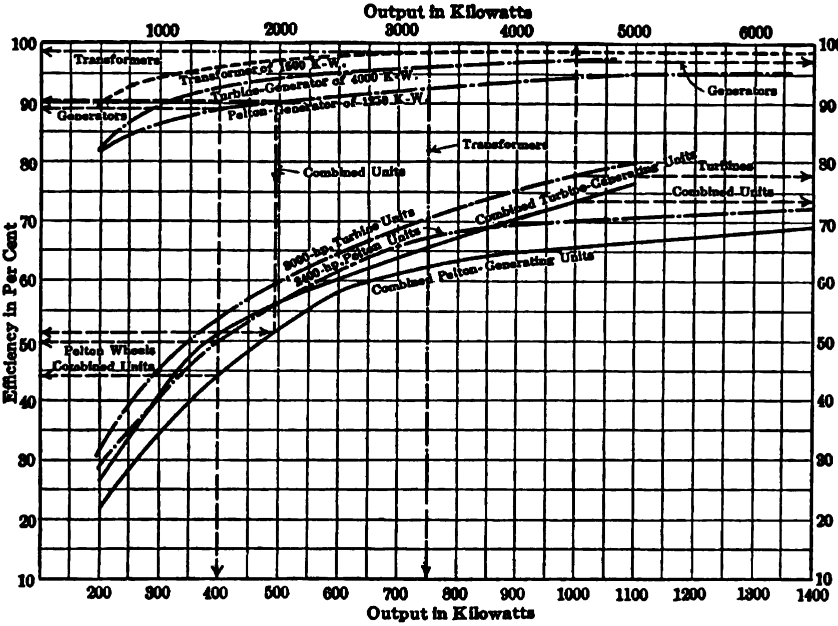


Fig. 105.—Water Wheel, Turbine, Generator and Transformer Efficiencies in Per Cent. for Different Kw. Loads at Generating Station

The input for each output throughout the year was computed from efficiencies of the tests, and may be taken from the curves given. The power used in excitation was computed from half-hour readings on the exciter outputs, and amounted to 1.3 per cent. of the output of the generators.

The step-up and step-down transformers were in circuit continuously to keep them in good condition. The core losses were found to be practically constant for all loads. The copper loss was computed from the switchboard instrument readings and reduced to kilowatt-hour values and kilowatts, the latter giving an average value of 2.54 kw. per transformer; the total average loss being 130 kw. for nine units, and the all-day efficiency

96 per cent. For the eight units at the receiving station the average total loss was 105 kw., with an all-day efficiency of 96.6 per cent.

For the year in which the above values were obtained, the following table gives the losses and efficiencies:

TABLE 11.—HYDROELECTRIC PLANT LOSSES AND EFFICIENCIES.

PARTS OF SYSTEM	ALL-DAY EFFICIENCY IN PER CENT.	INPUT IN KW. (AVERAGE VALUES)	LOSS IN KW. (AVERAGE VALUES)	LOSS IN PER CENT. VALUES	LOSS IN PER CENT. OF PENSTOCK INPUT (AVERAGE VALUES)
Penstocks	97.7	6009	130	2.3	2.3
Waterwheels	60.7	5795	2277	39.3	37.9
Generators	93.5	3518	227	6.5	3.8
Exciters	..	76	76	..	1.3
Step-up Transformers	96.1	3270	129	3.9	2.1
Transmission Line	98.6	3141	43	1.4	0.7
Step-down Transformers	96.6	3098	104	3.4	1.7

The transmission line loss was computed from the constants of the lines and the load data. The line resistances were measured by direct current, using the fall of potential method, which checked very closely with the computed value. The induction and capacity were computed by the usual method, and the all-day efficiency was calculated by means of the simple regulation diagram for both lines operating in parallel. The average yearly line loss (taken for one particular year as referred to here), figured from the regulation diagram, using half-hour readings at the receiving station for load data, was 43 kw. and the all-day efficiency 98.6 per cent.

CHAPTER IV

TRANSMISSION LINE CONSTRUCTION AND OPERATION

Line Structures.—Various conductor supports are used on transmission systems throughout the country including wood, steel and concrete poles and steel towers of various designs according to the required height and strength. The steel square base tower is largely used for main line high voltage lines with wood poles, patented steel poles and flexible steel towers used for circuits under 66,000 volts and for branch and distribution lines. Local conditions such as right-of-way, contour and the nature of the service from the line largely determine the conductor support for the medium transmission voltage. However, for lines of a permanent character, steel construction is fast becoming popular, since the cost per mile of the completed steel line compares favorably with that of wood. The merits of the steel pole in its several available forms for light lines demand consideration in all sections. Spans of moderate length can be used where the sag will not be too great and often a single pole be made to take the place of three or four wooden poles. While it is true that the former will cost more than three or four wood poles, the cost of insulators, pins and ties and of their erection as well as the cost of pole erection will be reduced in proportion to the number of poles saved. Again troubles from insulator failure are reduced by the reduction in their number and the item of line maintenance is generally in favor of the steel pole.

Construction Costs.—Comparative costs which may be accurate for a given set of conditions may give erroneous conclusions if applied elsewhere under conditions which differ widely. The following data is presented only as comparative and as rather typical construction. The information in Tables 12 and 13 is abstracted from an estimate prepared by R. D. Coombs and Company (*Electrical Engineering*, January, 1915) and gives a comparison between the cost of a short span wood pole line and a long span steel pole line. The line consisted of a $\frac{3}{8}$ in. steel ground wire, three 33,000 volt No. 2 copper conductors and two No. 10 copper clad telephone wires. For the wood pole construction 35 ft. poles with spans of 120 ft.—44 poles per mile—were considered, using metal cross arms and pin type insulators. The line ran through rolling country and was fairly easy of access for construction and inspection.

TABLE 12.—COST OF 33,000 VOLT WOOD POLE LINE.

		PER MILE
Poles.—		
Poles 35 feet long, 7 inch tops at $5.00		$220
Cross arms, galvanized and telephone brackets ($5 per mile)		172
Pole steps and hardware at $0.75 per pole		33
Framing and trimming at 0.50 per pole		22
Creosoting butts at 0.20 per pole		9
		$456
Hauling		44
Digging holes at $1.20	$53	
Bog shoes or braces	8	
Setting poles at $1.80	79	
	$140	$140
Guying		30
Wires and Line Material.—		$670
1 ground wire	$54	
3 conductors	544	
2 telephone wires	50	
	$648	
Ties and soldering materials ($5 per mile each)	10	
33000 V. insulators	66	
Telephone insulators	5	
Pins	50	
Ground wire connections	16	
Stringing wires	85	
	$880	
Clearing and trimming	10	
Miscellaneous materials and tools	15	
Right-of-way at $5.00	220	
Supervision, engineering and general expense	100	
Contingencies and incidentals	30	
	$1,255	$1,255
Total per mile of line		$1,925

TABLE 13.—COST OF 33,000 VOLT STEEL POLE LINE.

For the steel pole construction, 400 foot spans—13 poles per mile—with 3-disc suspension insulators were considered.

		PER MILE
Poles.—		
Poles and arms at $53.00		$698
Hauling at $2.25		29
Digging holes $1.50		20
Concrete at corners (including crushed stone at $6 per mile)		46
Erection at $2.25		29
Guying		30
Painting		20
Miscellaneous		7
Wires and Line Material.—		$870
1 ground wire	$54	
3 conductors	544	
2 telephone wires	50	
Soldering materials	5	
Insulators and clamps (telephone insulators at $5 per mile)	142	
Stringing wires	100	
Miscellaneous	15	
	$910	$910
Clearing and trimming		10
Miscellaneous materials and tools		20
Rights-of-way at $7.00		90
Supervision, engineering and general expense		100
Contingencies and miscellaneous		30
Total per mile of line		$2,030

While the totals of Tables 12 and 13 show little difference in first cost between the two types of construction, maintenance and allowance for depreciation favor the steel line.

Itemized costs for constructing two Ohio wood pole transmission lines, one insulated for 33,000 volts and the other for 13,200 volts, are given in Table 14. The 33,000 volt line is single-circuit construction, three-phase, 60 cycle, using No. 4 medium hard-drawn bare copper wire supported by 45,000 volt Ohio brass insulators on Washington fir cross-arms attached to wooden poles averaging 35 ft. in height. Both wood and steel pins are used. Galvanized $\frac{5}{16}$ in. Siemens-Martin stranded ground wire is supported on insulator brackets at the top of the poles and grounded every fifth pole. The data refer to only 20 miles of line running through rural territory in which pole rights had to be purchased and permission secured for cutting

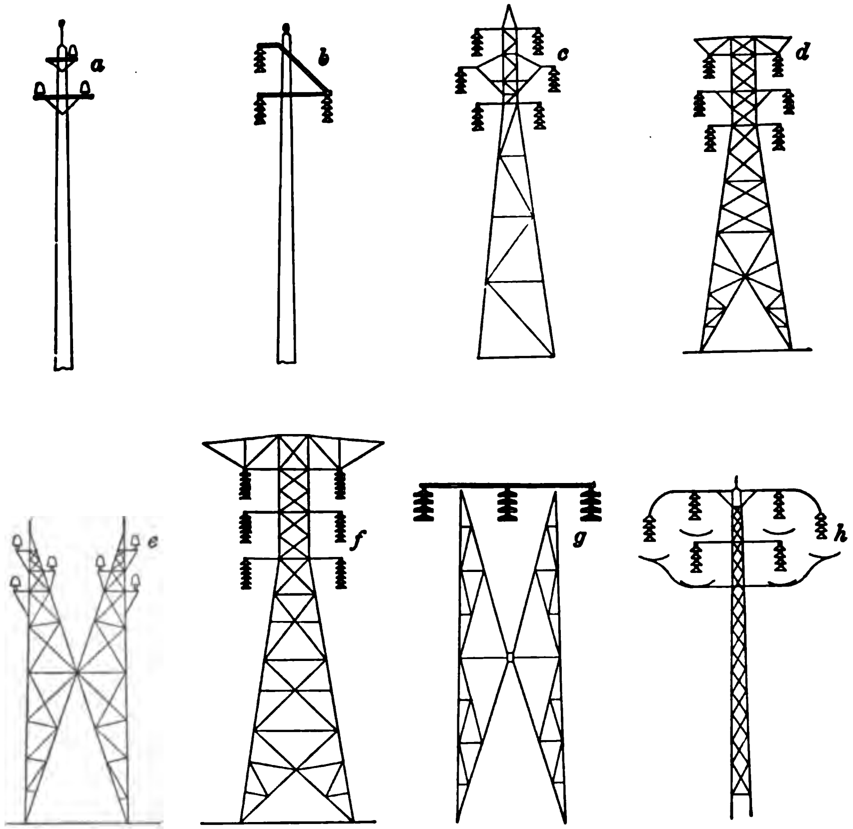


Fig. 106.—Types of Transmission Line Poles and Towers

Poles (a) and (b) are for voltages up to 60,000; (c), (d), (e), (f) and (g) are different types of towers for 60,000 to 110,000 volts, and (h) a steel pole suitable for city high tension circuits.

trees 50 ft. on each side of the line. The maximum pole height is 55 ft., the normal pole spacing 135 ft. and the maximum spacing, 175 ft.

The 13,200 volt line is 8 miles long, of the same construction as the 33,000 line and identical in poles and conductors except being insulated for a lower voltage. The line is run on the highway, no pole rights being required, but trees along the route needed considerable trimming. The 33,000 volt line was run on a private right-of-way.

Table 14.—Unit Costs per Mile of Two Wood Pole Transmission Lines

	33,000 Volt Line	13,200 Volt Line
Securing right-of-way	$41.40	$3.47
Pole rights	103.60	. .
Damages	66.45	3.46
Buying poles	2.22	. .
Inspecting poles	1.70	. .
Cleaning right-of-way	54.50	150.00
Pole costs	201.00	389.00
Hauling poles	7.58	Included in cost
Digging holes	31.80	46.00
Framing poles	8.25	16.50
Creosoting poles	3.08	1.97
Setting poles	25.28	72.70
Cross-arms (total)	78.39	54.13
Pins (total)	25.44	6.10
Insulators (total)	67.44	34.98
Ground-wire supports (total)	17.36	22.55
Telephone supports and insulators	6.12	None
Line hardware	25.60	23.40
Anchors and guys (total)	20.91	37.00
Conductors—three No. 4 copper:		
Material	342.00	261.00
Labor of stringing	45.10	46.40
Ground wire ($\frac{5}{16}$ Siemens-Martin):		
Material	57.50	39.60
Labor of stringing	14.00	15.00
Ground rods	6.08	4.27
Telephone wire:		
Material	20.60	None
Labor	14.30	None
Camp expenses and meals	83.22	None
Engineering and superintendence	134.22	68.90
General expense	55.60	184.35
Total cost per mile	$1,570.75	$1,480.48

Costs for Wood Pole and Tower Lines.—The data of the accompanying table show a comparison of the unit costs of building two Montana transmission lines which use the same size of line conductors and the same types of insulators, one line being of wood pole construction and the other of steel tower construction. Both lines operate at 100,000 volts, and were built under conditions which make them similar except in the use of supporting structures. The steel towers used are single circuit with horizontal crossarms. The wooden pole structures consist of two 45 ft. 8 in. cedar poles supporting a single horizontal crossarm. The copper costs for the two lines have been reduced to the same base price, and the other data were taken from construction records.

TABLE 15.—UNIT CONSTRUCTION COSTS PER MILE FOR TWO 100,000 VOLT TRANSMISSION LINES USING NO. 0 COPPER CONDUCTORS

WOOD POLE LINE	COST PER MILE	STEEL TOWER LINE	COST PER MILE
Pole structures	$203.80	Towers	$615.38
No. 0 copper wire	955.00	No. 0 copper wire	955.00
Ground wire	141.95	Ground wire	141.95
Telephone line	121.20	Telephone line	259.95
Insulators	239.50	Insulators	108.85
Cross arms	29.45		
Hardware	28.75		
Line switches	21.55	Switches	115.38
Creosote treatment	60.50		
Clearing	30.80	Unloading	14.23
Hauling	149.40	Hauling	181.33
Digging	61.20	Digging	165.55
Framing	40.20	Assembling	77.17
Setting	43.80	Setting	31.90
Stringing wire	87.50	Stringing wire	117.52
Guying	21.38	Guying	46.24
Guarding	3.59	Erecting	60.25
Survey	39.80	Survey	20.40
Camp	67.50	Camp	122.33
Tools	14.62	Tools	28.71
Roads	.13		
Hospital, injuries and damages	6.10		
Injuries during construction	.77		
General expense	55.00	General expense	128.52
Total	$2,423.49	Total	$3,189.76

Labor Cost in Transmission Line Construction.—The following division of costs is given by J. W. Fraser for the construction of a double circuit, 100,000-volt tower line using No. 2/0 copper conductors and built under conditions that prevail in the Carolinas. The spacing of towers was nine to the mile, eight suspension towers and one strain tower. The cost of right-of-way is not included in the figures.

TABLE 16.—ANALYSIS OF TRANSMISSION LINE CONSTRUCTION COSTS

CONSTRUCTION ITEM	PER CENT OF TOTAL COST
Towers	27
Insulators	8
Clamps	1
Ground wire	2
Conductor (6 No. 00 copper)	42
Labor	15
Interest during construction	3
Engineering, supervision, and surveying, general office expenses	2
	100

ANALYSIS OF LABOR COSTS FOR TRANSMISSION LINE CONSTRUCTION

LABOR ITEM	PER CENT OF TOTAL COST
Digging holes	23
Hauling and distributing towers	9
Assembling	8
Erecting	14
Filling in holes	7
Hauling and distributing insulators	8
Hauling and distributing wire	6
Stringing six conductors and one ground wire	25
	100

It is to be noted that by far the largest item is conductor, and that insulation is a comparatively small factor. It might be well to emphasize here that a small additional percentage cost of tower in comparison with total cost of line may add greatly to the factor of safety of the line.

Conductors.—The metals used for transmission line conductors include copper, aluminum, copper-clad steel (copper and steel welded), mechanical combination of aluminum and steel and to some extent steel alone. Copper and aluminum are used for power circuits, steel and copper-clad for ground wires and both copper and copper-clad for telephone lines. Steel and copper clad and to some extent steel core aluminum are used for long spans where high mechanical strength is required. The most extensive use of the steel core aluminum cable is by the Pacific Light and Power Company on its Big Creek line which is 240 miles long and operates at 150,000 volts. This cable is one inch outside diameter with a ⅜ in. steel core. The chief objection to aluminum is its relatively low tensile strength and high coefficient of expansion which require very careful attention and exacting allowances for sag to avoid overstraining. A comparison of the various characteristics of aluminum and copper wire and the basis on which to compare prices are given in the accompanying table.

TABLE 17.—COMPARISON OF CONDUCTIVITY OF COPPER AND ALUMINUM WIRE

Conductivity of Aluminum	63	62	61	60
Relative cross-section (copper equal 100)	154.	156.5	159.	161.7
Weight of aluminum (weight of copper of equal length and equal resistance equal 100)	46.8	47.6	48.3	49.1
Tensile Strength—Factor by which to multiply tensile strength per square inch of aluminum to obtain tensile strength per square inch required in a copper wire of equal resistance in order to secure same breaking strength	154.	156.5	159.	161.7
Price—Factor by which to multiply copper price per pound to obtain equivalent price of aluminum; also factor by which to divide aluminum price per pound to obtain equivalent price of copper	2.13	2.10	2.07	2.03
Price—Factor by which to divide copper price per pound to obtain equivalent price of aluminum; also factor by which to multiply aluminum price to obtain equivalent price of copper	.468	.476	.483	.491

For transmission lines hard drawn copper should have a minimum ultimate tensile strength of 50,000 lb. per sq. in.; aluminum a minimum tensile strength of 23,000 lb. per sq. in.; 40 per cent. copper-clad steel 100,000 lb. per sq. in.; and steel wire not less than 60,000 lb. per sq. in. All these metals are most used in cable form when larger than No. 6 B. & S. gage, since solid conductors for long spans tend to crystallize at the points of support due to constant swinging in the wind. Solid wires are, however, used up to No. 00, which is about the practical limit.

TABLE 18.—PHYSICAL PROPERTIES OF TRANSMISSION LINE CONDUCTORS

KIND OF MATERIAL	COPPER		ALUMINUM	COPPER CLAD		STEEL		
	Annealed	Hard		30 Per cent.	40 Per cent.	S-Martin	High Stgth	Ex. Hg. Stgth.
Per cent. Conductivity (Matthiessen's Standard)	99–102	96–99	61	29¼%	39%	8.7	. .	. .
Specific Gravity	8.89	8.94	2.68	8.25	8.25	7.85	7.85	7.85
Pounds in 1 cubic inch	.320	.322	.0967	.298	.298	.283	.283	.283
Pounds per 1000 ft. per circular mil.	.003027	.003049	.000920	0.00281	0.00281	.002671	. .	. .
Elastic Limit in lbs.	28,000	30–35,000	14000–16000	. .	. .	38,000	69,000	112,000
Ultimate Strength lbs. per square inch	32–34,000	50–67,000	23000–50000	60,000	100,000	75,000	125,000	187,000
Coefficient of Linear Expansion per ° C.	.0000171	.0000171	.0000231	.000012	.000012	.0000118	. .	. .
Coefficient of Linear Expansion per ° F.	.0000095	.0000095	.0000128	.0000067	.0000067	.00000662	. .	. .
Melting Point in ° C.	1100	1100	657	. .	. .	1360	. .	. .
Melting Point in ° F.	2012	2012	1215	. .	. .	2480	. .	. .

These specifications have been taken from a report by a sub-committee on overhead line construction of the National Electric Light Association.

Conductor Sizes.—The size of conductor for a transmission line depends upon a variety of conditions such as the load to be transmitted, voltage used, allowable drop in voltage in transmission, on account of resistance and inductance of conductors and the distance over which energy is transmitted. Mechanical considerations are also important and include pole spacing and ground clearance over irregular country. A chart for calculating conductor sizes and weights of metal is described on page 190 (Fig. 107).

The best voltage for a system, as far as a transmission line is concerned, is the highest that can be economically produced. This is on account of the fact that the laws governing the alternating current circuit show that the higher the voltage, the smaller the current for a given amount of power. Thus a small current on the line means that the size of conductor can be reduced until the mechanical strength of the wire used is the controlling factor. The use of high voltages reduces the line drop, the losses in transmission, and gives better regulation than lower voltages, yet calls for greater expense both in cost of material and construction. The selection of voltage, therefore, is an engineering consideration largely controlled by particular conditions and engineering judgment.

Spacing of Conductors.—The arrangement and spacing of conductors on poles and towers is influenced by the voltage, the length of the span, kind of conductors and insulators used and the relative position of the conductors. The best distance is just that which will allow lines to whip in the wind without touching, and be sufficiently far apart at the supports so as to prevent flashing during line disturbances. The increase in spacing increases the inductive drop and also the line loss. There are no fixed rules for spacing of lines on transmission poles and towers, however, the accompanying table shows average practice, in this regard.

TABLE 19.—TABLE OF MINIMUM SEPARATION OF LINE CONDUCTORS *

KILOVOLTS	DISTANCE GIVEN IN INCHES FOR SPAN LENGTH					
	150 ft.	250 ft.	350 ft.	500 ft.	650 ft.	800 ft.
Pin Insulators:						
Not exceeding 6.6	24	30	36	48	60	72
Over 6.6 to 22.0	32	37	42	54	65	76
" 22.0 to 44.0	46	50	56	64	74	82
" 44.0 to 66.0	58	62	66	72	82	88
" 66.0 to 88.0	72	74	78	84	90	96
Suspension Insulators:						
Not exceeding 44.0	48	56	62	72	86	100
Over 44.0 to 66.0	66	72	77	86	98	112
" 66.0 to 88.0	80	86	91	102	112	125
" 88.0 to 110.0	93	98	104	115	124	135
" 110.0 to 140.0	110	114	120	127	136	148
" 140.0 to 165.0	120	126	132	138	147	157
Dist. for vertical spacing.	12	15	24	24	30	30

* Recommendations of the Locke Insulator Manufacturing Company.

The amount of copper called for by any line depends upon the voltage, it being the general law that the amount of copper varies inversely as the square of the voltage; that is, if the voltage is doubled, the size of wire may be only one-quarter as great, all other conditions remaining the same. In calculating the size of conductors, it is poor policy to use a larger conductor than is absolutely required. The rule governing this is known as Kelvin's Law, and as usually used is stated as follows: "The most economical area of conductor is that for which the annual cost of the energy wasted is equal to the interest on that portion of the capital outlay which can be considered proportional to the weight of the metal used." (See discussion of Kelvin's Law, page 273.)

While copper and aluminum are the chief metals used for transmission of power, steel wire or conductors with steel center and copper or aluminum outside is used where great mechanical strength is required as in long transmission line spans or where diameter is essential to prevent corona formation. In the use of any metal for wires and cables, the elastic limit must not be exceeded by the weight of the wire between spans and the probable wind and sleet pressure. This condition is met in some cases by a factor of safety of two based upon the metal's ultimate strength.

The overhead line committee of the National Electric Light Association recommends the consideration of the following loads when designing lines: 1.—No ice and wind pressure of 15 pounds per square foot. 2.—Ice ½ inch thick, and a wind pressure of 8 pounds per square foot. 3.—Ice ¾ inch thick and a wind pressure of 11 pounds per square foot. The No. 2 loading gives greater stress than No. 1, and is best for use in most localities where ice formation is not a serious problem.

Table 20.—Data for Bare Copper and Aluminum Cable of Same Conductivity

B & S Gage or Circ. Mils.		Approx. Diam. in Inches		Number of Strands		Resistance per 1000 ft. at 77 F.	Weight-Lb. per 1000 Ft.	
Copper-(97%) Equivalent	Aluminum 61%	Copper	Alum	Copper	Alum		Copper	Alum
2,000,000		1.631		127		0.00539	6,180	
1,900,000		1.590		127		.00568	5,870	
1,800,000		1.548		127		.00599	5,560	
1,700,000		1.504		127		.00634	5,250	
1,600,000		1.459		127		.00674	4,940	
1,500,000		1.412		91		.00719	4,630	
1,400,000		1.364		91		.00770	4,320	
1,300,000		1.315		91		.00830	4,010	
1,200,000		1.263		91		.00899	3,710	
1,100,000		1.209		91		.00981	3,400	
1,000,000	1,590,000	1.152	1.437	61	61	.0108	3,090	1,462
950,000	1,515,000	1.123	1.406	61	61	.0114	2,930	1,393
900,000	1,431,000	1.093	1.359	61	61	.0120	2,780	1,317
850,000	1,351,500	1.062	1.328	61	61	.0127	2,620	1,243
800,000	1,272,000	1.031	1.281	61	61	.0135	2,470	1,171
750,000	1,192,500	.998	1.250	61	37	.0144	2,320	1,098
700,000	1,113,000	.964	1.203	61	37	.0154	2,160	1,025
650,000	1,033,500	.929	1.156	61	37	.0166	2,010	950
600,000	954,000	.893	1.109	61	37	.0180	1,850	877
550,000	874,500	.855	1.062	61	37	.0196	1,700	805
500,000	795,000	.814	1.015	37	37	.0216	1,540	732
450,000	715,500	.772	1.031	37	37	.0240	1,390	658
400,000	636,000	.728	1.906	37	37	.0270	1,240	585
350,000	556,500	.681	1.859	37	19	.0308	1,080	512
300,000	477,000	.630	1.781	37	19	.0360	926	439
250,000	397,500	.575	1.718	37	19	.0431	772	365
0,000	336,420	.528	1.656	19	7	.0509	653	310.2
000	266,800	.470	1.578	19	7	.0642	518	245.7
00	211,950	.418	1.515	19	7	.0811	411	195.0
0	167,800	.373	1.468	19	7	.102	326	155.0
1	133,220	.332	1.406	19	7	.129	258	122.6
2	105,530	.292	1.359	7	7	.162	205	97.2
3	83,640	.260	1.328	7	7	.205	163	77.0
4	66,370	.232	1.296	7	7	.259	129	61.2
6	41,740	.184	1.234	7	7	.410	81	38.5

These values are taken from tables compiled by U. S. Bureau of Standards for copper cable and by Aluminum Company of America for aluminum cable.

As an example of transmission line construction typical of advanced tendencies in design and operation, it is of interest to review the notable features of the world's longest (241 miles) and highest voltage (150,000 volts) transmission line. In the first place, the system is in complete duplicate, consisting of two steel-tower lines, erected 80 ft. apart, each carrying a single three-phase circuit, the wires of which are supported in a single horizontal plane, each by nine disc insulators in series. The towers used are of very moderate height, only 43 ft. to the cross-arm from which the suspension insulators are carried, and are placed also at moderate intervals, being on the average 660 ft. apart. The line conductors are carried rather low, as little as 25 ft. in the center of the spans, a height which would seem precariously low in a more thickly settled country. The general nature of the structure, however, is such as to give unusual stability to the line, and since the circuits are on a private right-of-way 150 ft. wide, the lack of height may be justifiable. The spacing between conductors is at the record distance of 17.5 ft., and wherever necessary the conductors have a tension mooring to the structure through a string of nine insulators to check lateral swaying of the conductors. It is also of interest to note a disregard of induction due to wide spacing in the construction of this line. In fact, added inductance is rather a good thing in view of the unavoidable capacity effects on such a line. The conductors themselves are of unusual size and character, being aluminum cable laid over a stranded steel core. The over-all diameter of the cable is 0.95 in. and the weight about 2 tons per mile. Each tower line carries on its top a galvanized-steel cable serving as an earthed wire in accordance with the general practice to which reference has been made.

Graphical Solution of Transmission Line Problems.—The analytical solution of transmission line problems is a tedious operation, and various graphical methods have been devised to facilitate the solution and minimize as far as possible the time and labor required. These methods are based, primarily, on the factor of voltage drop, or regulation, but do not, in most cases, take into account the charging current of the line and their use is, therefore, limited to relatively short lines of moderate voltage where the condenser effect of the circuit may be neglected. As solutions of the problem in the form in which it generally occurs in practice they are indirect, requiring the assumption of the size of wire in advance, and from one to several trials, before the correct size is found, or else a conversion of the problem into terms of a single-phase equivalent. In all cases, more or less supplementary calculation is required, the graphical solution being only a partial one.

A method by H. B. Dwight, published in the *Electrical World* of January 16, 1915, however, gives a direct solution based on voltage drop for the problem in either form, i. e., it is possible to find the size of conductor with a given voltage drop or conversely to determine the regulation when the size of wire is given. By means of a simple correction factor the capacity effect is allowed for and the range of the chart is extended to lines up to 100 miles in length, with a close accuracy.

With the increasing use of synchronous condensers for the control and regulation of voltage drop independently of the size of conductor, the inherent regulation characteristics of the line become of relatively less importance in the design of present-day systems. This factor, as affecting the choice of conductors, is wholly eliminated in the case of constant voltage transmission systems, in which the voltage may be maintained not only constant but equal at the generator and receiver ends of the line. In these cases the allowable limit of energy loss becomes the sole criterion in determining the size of conductor unless, where the smaller sizes of wire are called for, corona effect or the limiting size for mechanical strength may require consideration.

One of the most recent and convenient graphical solutions of the formula commonly used for the total weight of conductor in a three-phase transmission circuit has been devised by T. A. Wilkinson of Westinghouse Church, Kerr and Company. By courtesy of the author a chart and a discussion of it are presented here taken from the *Electrical World*, August 12, 1916. The chart shown is based upon the allowable limit of energy loss in per cent. of the power delivered. The formula is

$$W = \frac{KPl^2}{pV^2F^2}$$

where W is total weight of conductor; P is power delivered; l is transmission distance; p is energy loss in line, in per cent. of power delivered; V is receiver line voltage; F is load power factor; K is a constant, depending on the system of transmission, conductor material and units used.

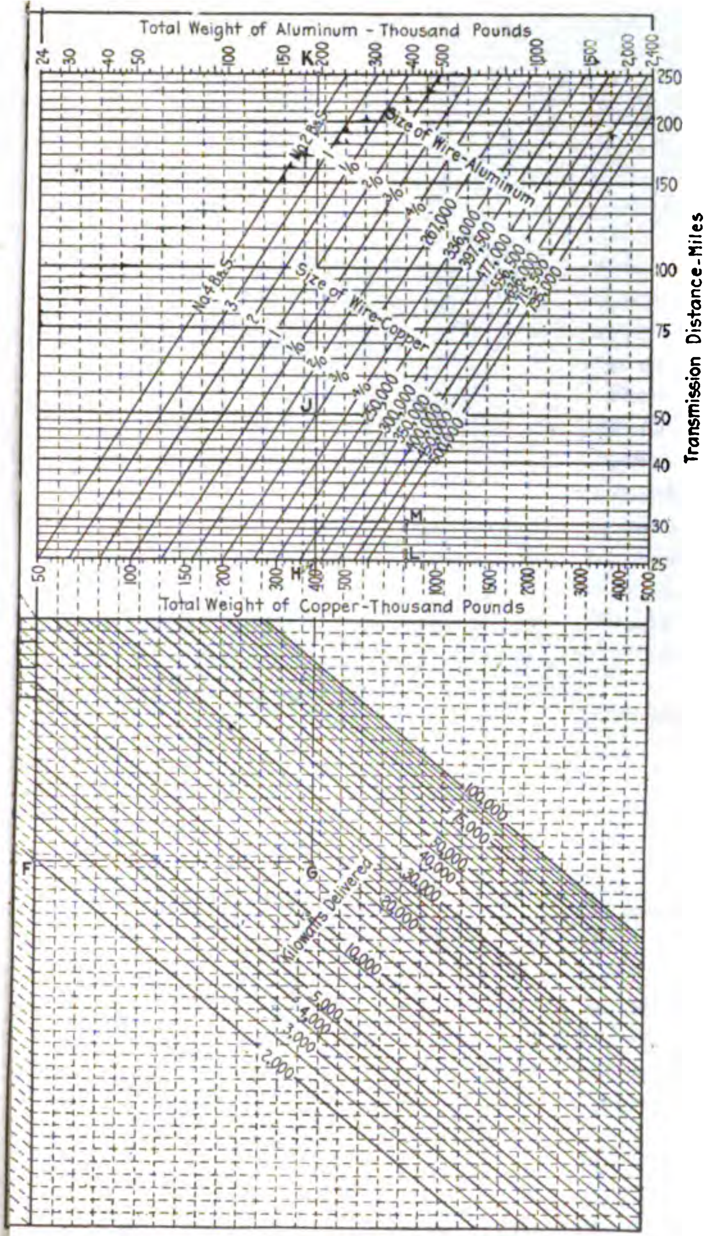
For a three-phase system with copper conductors, and the units shown on the chart scales, the constant is 262,500, and the formula becomes

Total weight of copper (thousand pounds)

$$= \frac{262{,}500 \times \text{kilowatts} \times (\text{miles})^2}{\text{per cent. energy loss} \times (\text{volts})^2 \times (\text{power factor})^2}.$$

Use of the Chart.—The method of using the chart is indicated by the solution of the following problem: What is the size and total weight of wire for a three-phase copper circuit to deliver 16,000 kw. a distance of 50 miles at 60,000 volts, with a line loss of 10 per cent. of the delivered power, the power factor of the load being 0.85?

Beginning at A (50 miles), follow the course of the broken line successively through the points B, C, D, E, F, G, representing the above given values of the different quantities and two intermediate reference points. At H, vertically above G on the lower weight scale, will be read the total



Transmission Lines

(Facing page 100)

weight of copper required, namely, 400,000 lb. Continuing vertically upward to an intersection at *J*, with the horizontal line at 50 miles, the size of wire, 3/0, will be read on the diagonal through *J*. Should the point *J* fall between the two diagonals, the point should be shifted to the right or left to intersect the next larger or smaller size, as may be desired. The point *H* will be shifted correspondingly, and the weight of conductor for the gage size chosen will be read vertically below the new position of *J*.

Due to the convenient practical relation existing between the sizes of copper and aluminum conductors of equal conductivity, the use of the chart is extended in a very simple way to include aluminum conductors. The relative conductivities of commercial copper and aluminum for equal cross-section are approximately as 97:61, or as 1.59:1. This is the ratio of cross-section and conductivity between copper wires two gage sizes apart. The equivalent of a copper conductor of a given size, therefore, is an aluminum wire two sizes larger. Each diagonal may thus represent either a copper conductor or an aluminum conductor of equivalent size. The corresponding sizes of copper and aluminum are indicated on the diagonals. While for practical reasons the above relation is assumed in the construction of the chart, it should be stated that the copper wire scale is based, as is more fully noted below, on a conductivity of 100 per cent. The assumed relation in size is therefore only strictly true for aluminum of a conductivity of $100 \div 1.59 = 63$ per cent., or 3 per cent. higher than that of commercial hard-drawn aluminum. As the difference in cross-section and weight of consecutive gage sizes of wire is 26 per cent., this small difference can have no effect on the choice as between one gage size and another.

The relative weights of a copper conductor and an aluminum conductor two gage sizes larger are as 100 to 48, and the total weights for equivalent aluminum conductors are given on the upper weight scale, the value at any point on the aluminum scale being 48 per cent. of the corresponding point on the copper scale. In the example used the size of the equivalent aluminum conductor is 267,000 circ. mil., and its weight, read at *K* on the upper scale, is 195,000 lb. The exact weights of copper and aluminum based on the formula are 403,700 lb. and 193,800 lb. respectively.

Range of Chart.—While the chart is intended primarily to cover the range of high tension transmission line practice, the range can be extended very simply to cover lines of any length or voltage beyond the range shown on the scales. This will be clear from the following considerations.

By reference to the formula it will be noted that the total weight of conductor is proportional to the quantity $\frac{\text{miles}^2}{\text{volts}^2}$, or inverting the fraction, the weight is inversely proportional to $(\text{volts per mile})^2$. Any combination of line voltage and miles, therefore, in the same ratio as the actual case will require the same total *weight* of conductor. All that is necessary, therefore, in the case of a short line is to multiply the volts and miles by a number that will bring the problem within the range of values on the chart. Simple multiples of two, five or ten will meet practically all cases.

In finding the size of conductor corresponding to the weight determined as above, it will be noted that the weight as determined is for a line $1/N$ times as long as the multiplied value, where N is the multiplier used. This is equivalent to saying that for a line of the multiplied length the weight will be N times the weight found. By multiplying the actual weight, therefore, by N, and locating this value on the scale, the size of conductor will be found vertically above it at the intersection with the horizontal line for the multiplied length of line. To illustrate, assume the following conditions where, in order to avoid confusion, only the distance and voltage are changed from the first example:

Transmission distance	15 miles
Voltage delivered	18,000
Energy loss, per cent.	10
Power factor of load	.85
Kilowatts delivered	16,000

To find the weight and size of copper required, by using a multiple of two with the derived values of miles and voltage, 30 miles and 36,000 volts respectively, proceed as in the original example. The new point *B* will be at the same vertical height as before (this height representing volts per mile) and the line *B*, *C*, *D*, *E*, *F*, *G*, *H* will coincide with the original problem, the weight of copper being 400,000 lb. as before. This is now the actual weight for a line 15 miles long. Multiplying by two we get a derived weight of 800,000 lb. (point *L*). At *M* vertically above *L* on the horizontal line at 30 miles the size of conductor is found to be about 550,000 circ. mil.

By means of the chart any one of the quantities involved, other than the length of line, can be found if the remaining quantities are known. For instance, referring to the first example given, assume that the problem had been to find the per cent. energy loss in a three-phase 3/0 copper circuit 50 miles long, delivering 16,000 kw. at 60,000 volts, with a load power factor of 0.85. Beginning at *A*, follow the broken line to *B*, which defines the position of a line horizontally to the right. Beginning at *J*, follow the broken line in a reverse direction through *G*, *F*, *E*, *D*, thence diagonally upward to an intersection with the horizontal from *B*. The intersection of these lines will be at the point corresponding to the per cent. energy loss, in this case, of course, at *C*, 10 per cent.

Single and Two-phase Solutions.—Problems in single-phase and two-phase transmission can be readily solved. For equal energy loss, under the same conditions of voltage and power delivered, a single-phase circuit will carry one-half the power, and a two-phase circuit will carry the same amount of power as a three-phase circuit having the same size of wire. To find the size of wire for a single-phase line, therefore, proceed as if for a three-phase circuit carrying twice the power. As there are only two wires, however, instead of three, the weight found by the chart must be reduced by one-third. To calculate a two-phase circuit, find the size of wire, for a three-phase line of equal capacity, and to the corresponding weight add one-third to allow for the fourth wire.

The necessary adjustments of weights described above for the solution of the special cases can very conveniently be performed graphically. To multiply the weight found for short lines by the factor N, simply measure to the right of the point H a distance equal to that between the scale value 100 and the values 200, 500 or 1000, according to whether the factor N is 2, 5 or 10, etc. This will give the point L, above which will be read the size of wire at M. To correct the weight value for a single-phase circuit measure to the left of the point H, as found for the three-phase circuit, the distance between the scale values 300 and 200. To correct for two-phase circuits measure to the right of H, a distance between the scale values 300 and 400. These adjustments, which reduce the original weight in the proportion of three to two and increase it in the proportion of three to four respectively, are simply the familiar processes of multiplication and division by the graphical addition and subtraction of logarithmic values.

Calculations for the copper weight scale are for solid wire throughout, and are based on the international annealed copper standard at 20 deg. C. This standard is defined and very complete wire tables based thereon are given in Circular No. 31 of the U. S. Bureau of Standards (October, 1914, edition). From this standard basis a single percentage correction can most conveniently be made to incorporate all of the allowances required for other conditions of temperature and conductivity, stranding, sag, etc., to meet any particular case. This correction can be made graphically in the same manner as described above by measurements from the reference point 100 on the weight scale.

Variation of True Power Loss and I^2R.—It should be noted that the chart is based on the load current I^2R losses in the conductor, and is exact throughout its range for these losses only. The true power loss, as calculated by the hyperbolic theory of transmission lines, and which includes the dielectric losses, is governed by the reactive conditions of the circuit. It may be more or less than the load current I^2R loss, the departure from equality depending on the length of line, frequency, power factor and current, and being greatest with long lines, high frequency, low power factor and small currents.

As the chart is intended primarily to facilitate the determination of conductor sizes, and this determination will be based, in most cases, on full load conditions, the ratio between the two losses at light loads is of minor importance. Also, with long lines means of regulation will be used to avoid low power factors. These conditions all favor the accuracy of the chart for its main purpose. Where precise results are desired and analytical calculation is necessary, its use will eliminate a good deal of waste effort, since all possible conditions can be quickly covered and the range for exact analysis much restricted. The limiting values of the ratio of true loss to I^2R loss within the extreme range of conditions covered by the chart and commercial frequencies, are shown in Table 20a for a 200-mile circuit of 500,000 cm. copper, under various conditions of power factor, frequency and I^2R loss. For all ordinary cases the ratios will be much closer to unity.

TABLE 20A.—LIMITING VALUES OF RATIO OF TRUE LOSS TO I^2R LOSS FOR A PARTICULAR LINE

POWER FACTOR	FREQUENCY	RATIO—TRUE LOSS TO I^2R LOSS			
		% I^2R Loss 3	5	10	15
Unity	25	1.02	0.99	0.98	0.98
	60	1.22	1.02	0.97	0.95
0.7 Leading	25	1.43	1.22	1.10	1.05
	60	2.25	1.63	1.20	1.12
0.7 Lagging	25	0.70	0.78	0.88	0.92
	60	0.61	0.63	0.75	0.80

CONDUCTOR SAG AND STRESS DETERMINATIONS

The chart[*] shown in Fig. 108 was devised by Percy H. Thomas. It gives to three scales the relations between sags and lengths of conductor and the stresses in the conductor at the point of support for a 1 ft. span when the conductor has a total weight of 1 lb. per foot. The quantities of sag, length

TABLE 21.—DIRECTIONS FOR USE OF CHART AND SYMBOLS

	ON CHART	IN SPAN	WITH ICE AND WIND
Sag, in feet	d	D†	. .
Stress, in pounds	s	S	S_i
Span, in feet	1	X	. .
Conductor loading, pounds per foot	1	W	W_i
Conductor length, in feet	l	L	l_i, L_i
Length unstressed, in feet	l_0	L_0	. .
Difference in height of supports, in feet	. .	T	. .
Area conductor, in square inches	. .	A	. .
Modulus of elasticity, pounds per square inch, is the stress necessary to double the length of sample	. .	M	. .

† Sag measured from higher point of support where a difference exists.

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[*] The chart is reproduced from a paper in the *Transactions* of the American Institute of Electrical Engineers, Vol. XXX, entitled "Sag Calculations for Suspended Wires," by Mr. Percy H. Thomas.

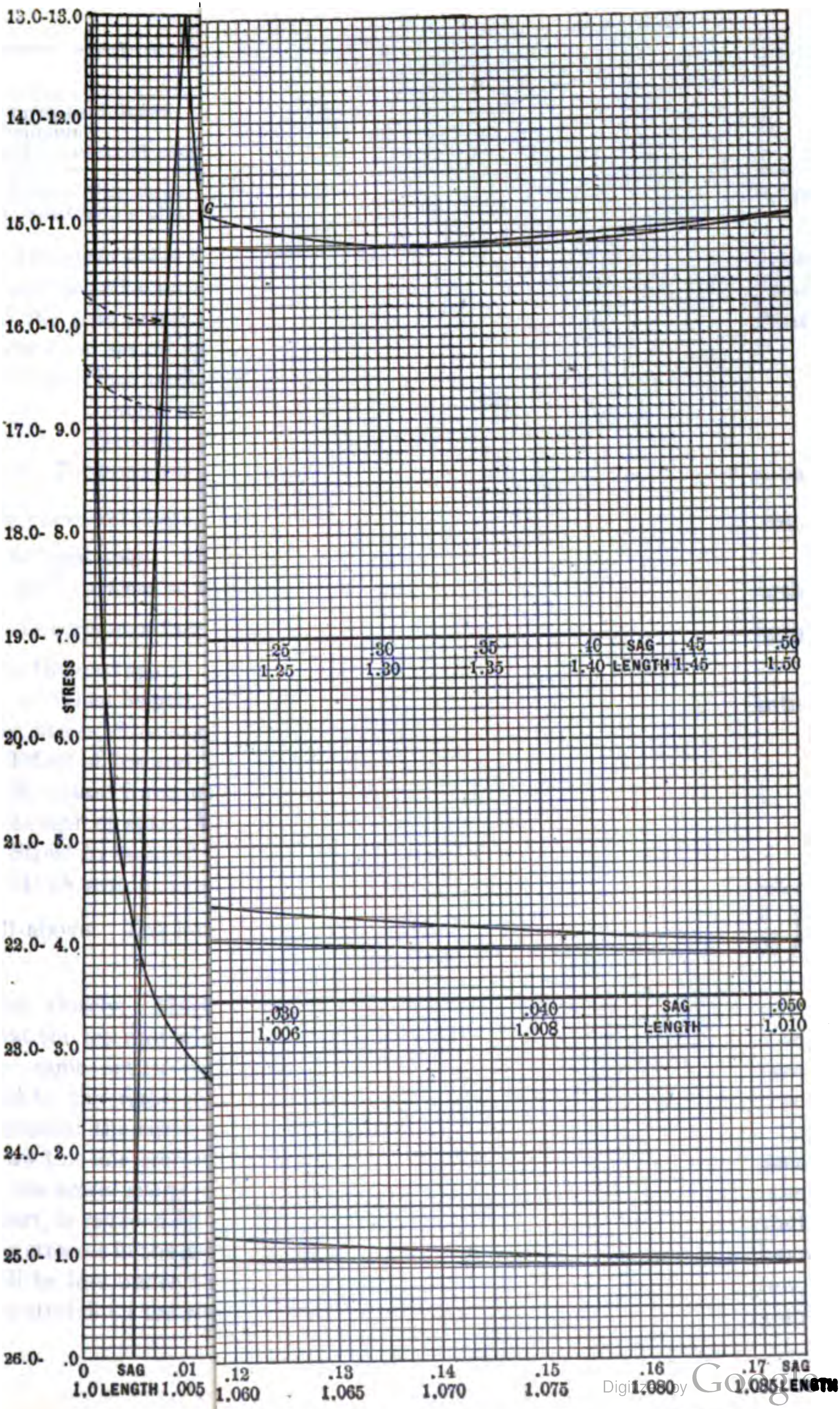

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TABLE 22.—APPROXIMATE PHYSICAL CONSTANTS

	MODULUS	TEMPERATURE COEFFICIENT
Copper, hard-drawn	16,000,000	0.0000095
Aluminum	9,000,000	0.0000128
Steel (Siemens-Martin)	29,000,000	0.0000066

NOTE.—The above figures are taken from the report of the committee on overhead line construction of the National Electric Light Association, 1914, Section III.

and stress in this 1 ft. span are directly proportionate to the same quantities in any actual span of similar shape. The curves on the chart are calculated by the true catenary formula and may be used for obtaining numerical values for actual spans.

Given, The loading of conductor per foot, W.
Length of span, X.
Stress to be used at support, S.

(1) *To determine the sag in actual span, D:* Find stress ordinate, s, on sag curve on chart, $s=\frac{S}{WX}$, and read sag as abscissa; this gives the sag, d, for unit span. Actual sag, $D=dX$.

(2) *To determine the length of actual conductor, L:* Find abscissa on length curve corresponding to the ordinate $s=\frac{S}{WX}$ as above; this gives the length l, in the unit span. Actual length, $L = l X$.

(3) When length, L, or sag, D, is given, the other corresponding quantities, stress, S, or sag, D, may be found by reversing the above process.

Effect of Ice and Wind.—Assume that the following items are given:
Resultant force on conductor per foot with ice and wind pressure, W_i.
Length of span, X.
Stress to be used at support, S.

(4) Determine length, l_i, in unit span from length curve on chart as under (2) above. The length unstressed, l_o, will be $l_o=\frac{l_i}{1+\frac{S}{AM}}=l_i\left(1-\frac{S}{AM}\right)$ very closely. Mark this value on chart on axis of X. Assume now that the ice and wind are removed. To determine the sag and stress on the same actual conductor in the new condition, draw a line upward and to the right from the point on the axis of X just determined, to represent the curve of stretch of the conductor with varying stresses. To draw this line proceed as follows: Since divisor W, used for reducing stresses in the *actual spans* to the stress, s, in the similar *1 ft. span*, as shown on the chart, is reduced by some definite factor R by the removal of ice and wind the stresses in the *actual conductor* represented by a given point on the chart will be less under the no ice and wind condition by the factor R. Now, the stretch on the chart at any stress ordinate, s, under the no ice condition

measured on the chart will be $\frac{sW}{AM}$. When this stretch is added to the length l_o one new point on the stretch curve has been calculated and when taken with the point, l_o, just marked on the axis of X, it will enable the line of stretch to be drawn as a straight line on the face of the chart. Where this stretch line cuts the length curve is the actual length that will be assumed in the chart on the removal of ice and wind. From this length the quantities sag and stress in the actual span can be readily obtained as specified under heading (3).

If it so happens that, in attempting to draw the stretch line, the length of unstressed conductor, l_o, is less than 1 ft. and hence falls off the chart, the stretch curve may be obtained by calculating two points on this curve as above, so selected as to fall conveniently on the chart. The straight line through these two points will constitute the stretch line.

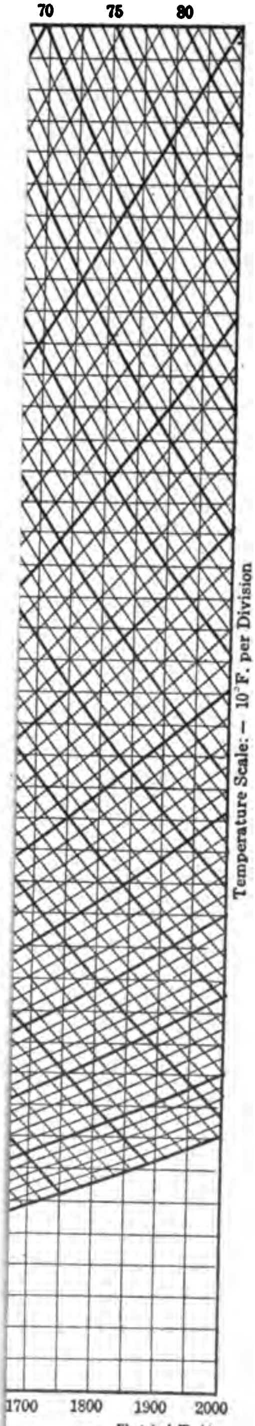
The effect of any intermediate condition of loading can be similarly obtained by starting with the unstressed length, l_o, and the desired value of the loading, W.

Effect of Temperature.—Having given the unstressed length, l_o, as determined above, for any given temperature, and assuming the loading to remain constant, to get the conditions for another temperature it is necessary only to determine a new unstressed length for any other desired temperature (by adding the calculated expansion for the change in the temperature) and to draw a new stretch line for this new temperature parallel to the first.

Where a range of temperature is to be studied it is very convenient to draw on the face of the chart a number of equally spaced parallel lines through a series of unstressed length abscissas corresponding to equal increments of temperature.

Unequal Heights of Supports.—If the supports at the ends of the spans have unequal heights, assume that the distance from the higher support to the lowest point of the span represents one-half the length of an equivalent symmetrical span. The distance from the higher support to the lowest point is $x_1=\frac{X}{2}+\frac{TS}{XW}$, where T is the difference in heights of the supports in feet and S the stress in the conductor. Where the sag, D, is given, the formula is $x_1=X\frac{\sqrt{D}}{\sqrt{D-T}+\sqrt{D}}$. The length of the equivalent span is 2 x_1, and the calculation of stresses, sags, lengths, etc., can then be made as before.

Sags and Stresses in Aluminum Conductor Spans.—The chart shown in Fig. 109 for determining the stresses and deflections in aluminum conductor spans was devised by the British Aluminum Company, Limited, of London, England. It is based upon the laws of the elastic catenary, assuming that



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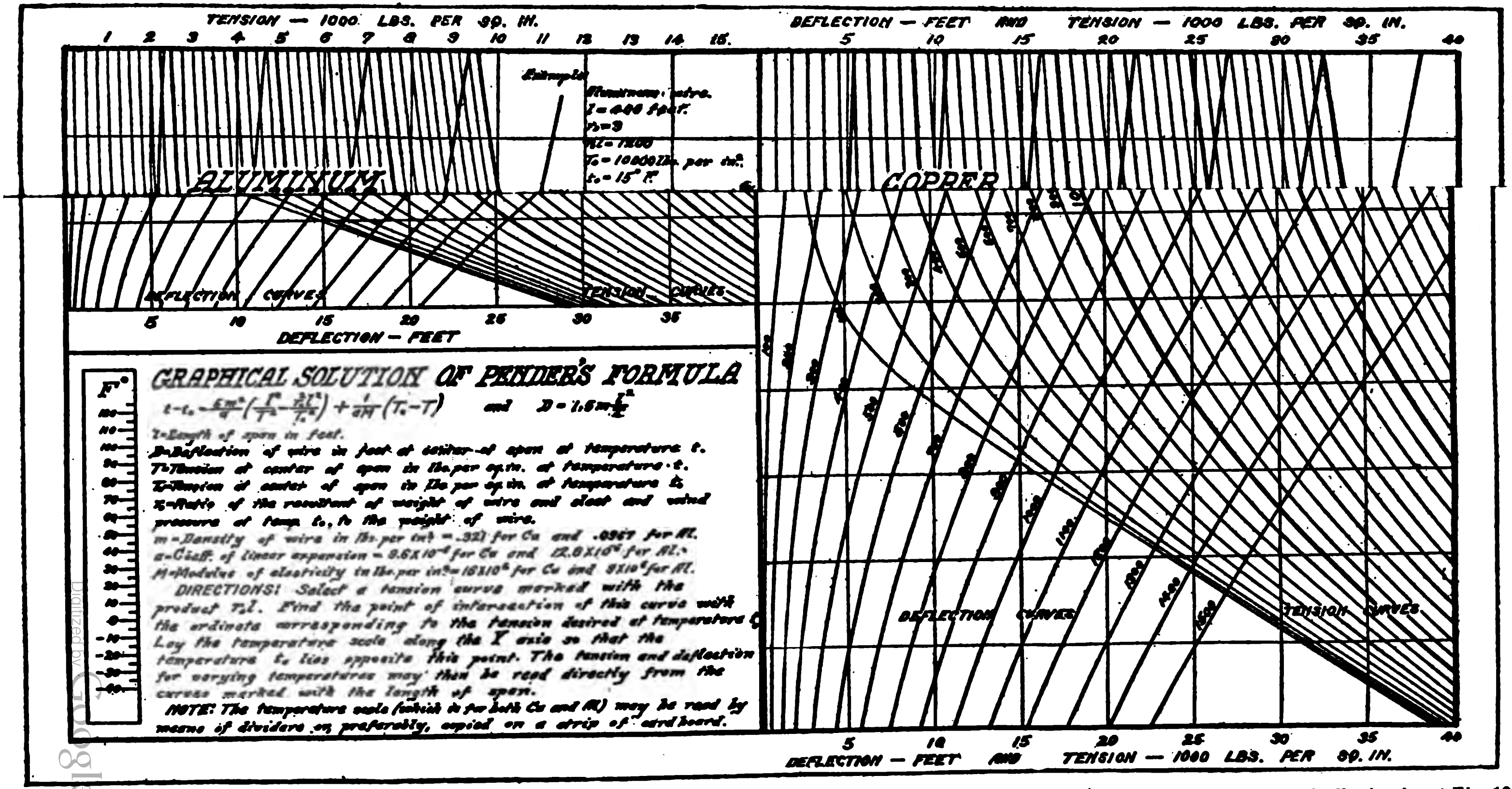


GRAPHICAL SOLUTION OF PENDER'S FORMULA

$t-t_0=\frac{l^2m^2}{24a}\left(\frac{r^2}{T^2}-\frac{r_0^2}{T_0^2}\right)+\frac{1}{aM}(T_0-T)$ and $D=1.5m\frac{l^2}{T}$

l = Length of span in feet.

D = Deflection of wire in feet at center of span at temperature t.

T = Tension at center of span in lbs. per sq. in. at temperature t.

T₀ = Tension at center of span in lbs. per sq. in. at temperature t₀.

r₀ = Ratio of the resultant of weight of wire and sleet and wind pressure at temp. t₀, to the weight of wire.

m = Density of wire in lbs. per in³ = .321 for Cu and .0967 for Al.

a = Coeff. of linear expansion = 9.6×10⁻⁶ for Cu and 12.8×10⁻⁶ for Al.

M = Modulus of elasticity in lbs. per in² = 16×10⁶ for Cu and 9×10⁶ for Al.

DIRECTIONS: Select a tension curve marked with the product T₀l. Find the point of intersection of this curve with the ordinate corresponding to the tension desired at temperature t₀. Lay the temperature scale along the Y axis so that the temperature t₀ lies opposite this point. The tension and deflection for varying temperatures may then be read directly from the curves marked with the length of span.

NOTE: The temperature scale (which is for both Cu and Al) may be read by means of dividers or, preferably, copied on a strip of cardboard.

Fig. 110.—Dr. Harold Pender's Chart for Sag and Stress Calculations

(Following insert Fig. 109)

aluminum has a modulus of elasticity equal to 9,000,000 lb. per square inch, a coefficient of linear expansion of 0.0000130 per 1 deg. Fahr. and a weight of 1.175 lb. for a bar 1 ft. long and 1 sq. in. cross-section. The use of the chart, shown in the accompanying figure, may be explained by means of the following concrete examples:

Assuming constant temperature, the intercept of the ordinate corresponding to a given length of span with the curve of desired stress (pounds per square inch) lies also on the curve of corresponding sag or deflection. For example, taking a span of 700 ft. and a unit stress of 10,000 lb. per square inch the intercept lies on the curve which corresponds to a sag of 7.2 ft. Temperature effects are easily cared for by increasing the vertical ordinate, in case of a rise of temperature, one division for each 10 deg. Fahr. If a rise of 70 deg. Fahr. is assumed in the last example, the sag becomes 11.8 ft. and the tension 6100 lb. per square inch.

TABLE 23. VALUES OF q, FOR ALUMINUM CONDUCTORS

WIND PRESSURE IN POUNDS PER SQUARE FOOT	CROSS-SECTION OF CONDUCTOR IN SQUARE INCHES								
	0.1	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6
10	1.98	1.51	1.32	1.22	1.17	1.14	1.12	1.10	1.09
20	3.58	2.61	1.99	1.72	1.57	1.48	1.41	1.36	1.32
30	5.21	3.48	2.77	2.33	2.08	1.92	1.79	1.71	1.64

Wind pressures are taken into account by means of a factor q, which is the ratio of the total load per linear foot to the weight of conductor per foot. If p is the effective wind load per linear foot and w is the weight per foot,

$$q=\frac{\sqrt{w^2+p^2}}{w}$$

The manufacturer employs a reduction factor of 0.6 in. computing the wind pressure on a cylindrical surface from a known or assumed pressure on a normal flat surface of the same projected area. Employing the formula just given and the reduction factor of 0.6, the values of q have been computed, as shown in the accompanying table.

Taking again the example first given and assuming a normal wind pressure of 30 lb. per square foot on a conductor having a cross-section of 0.6 sq. in., the procedure is first to find the value of q from the table, which is 2.33, and then multiply this factor by the span length, which gives $700\times 2.33=1631$. Next take this product, 1631, as the new span length and proceed as before. The new sag is found to be 39 ft., but this value must be divided by the factor 2.33, which gives 16.7 ft. as the correct deflection under the assumed conditions of wind loading, with a unit stress of 10,000 lb. per square inch.

The deflection which the span in the last example will assume in still air can be found by following the horizontal line through the point just determined until it intercepts the ordinate corresponding to the true span of 700 ft., which gives a sag of 13.6 ft. and a stress of 5,300 lb. per square inch. Charts similar to this one for aluminum can be constructed from the theory of the elastic catenary for any other conductor material, such as copper, steel or bronze.

Transmission Line Insulators.—Power companies are beginning to realize that the insulator is perhaps the most important item of a modern transmission line, for upon it depends the reliability of the company's service to its customers. For transmission purposes at this time, porcelain insulators can be classified as one piece, multi-part pin types and suspension types. The one piece insulator is used generally for voltages up to 20,000 volts. The multi-part insulator can be used to 80,000 volts, while beyond this voltage the suspension types have taken the place of multi-part pin types.

In the beginning, the modern high-tension insulator was a petticoat insulator of the same cylindrical form as low voltage telephone and telegraph insulators used, but slightly larger in dimension. Surface insulation was considered the vital point and the designs were made accordingly. Later developments brought about the incline of the petticoat outward, getting same further away from the bolt and keeping the inner surface dry. The weight and complications of manufacture in this regard thus brought about the multi-part insulators cemented together.

In the selection of an insulator of the pin type to operate under certain pressures, consideration must be given to the mechanical features involved, and also the internal electrical conditions of the system; the climatic conditions, such as long rainy seasons, salt storms, fogs, dust, lightning storms, etc. Experience has taught the transmission line engineer some undesirable features of an insulator, yet it has required long and careful work on the part of manufacturers to develop economical and efficient designs, and it is usually best to specify performance, and have the manufacturer furnish insulators to meet conditions of service to be rendered. The specifications for multi-part insulators usually itemize the tests for performance and in some cases specify in detail the manner in which they are to be applied. For dry flash-over as a rule 2½ to 3 times the rated line voltage is specified. And for the wet flash-over 1½ to 2 times the rated line voltage. A puncture test of usually 75 per cent. of the full rated line voltage, applied to the different shells separately before assembling. Very often, too much attention is given the wet flash-over test values that are obtained on insulators, and too little attention paid to dielectric strength and surface resistance to meet line conditions. Further data are given under the heading, "Puncture and Flash over Ratio for Insulators."

Suspension Insulators.—A great number of different designs of suspension type insulators are offered by manufacturers, but in general two types have been widely used. The interlinking type and the one piece disc type with a metal cap and center pin cemented to insulators. The first design has the advantage that in case the insulator breaks the wires will hold the other units together, and in good many cases prevent a shut down, but against this there is the possibility of their breaking from constant rubbing in the holes. In the one type the insulator is in tension, while the interlinking type is in compression. In general the principles of design of pin insulators are applicable to the suspension insulator, since the latter may be considered a modification of the former. In the early designs of suspension units, a disc type without petticoats was employed, but the latter designs make use of concentric circular ribs or petticoats on the under surface. The addition of the petticoat raises the sparking voltage 35 per cent. and at the same time increases the surface resistance of the insulator in wet weather.

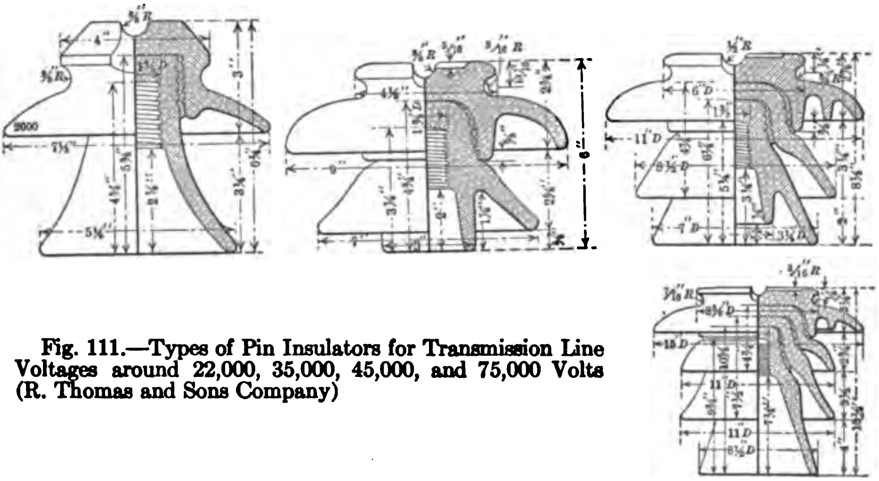
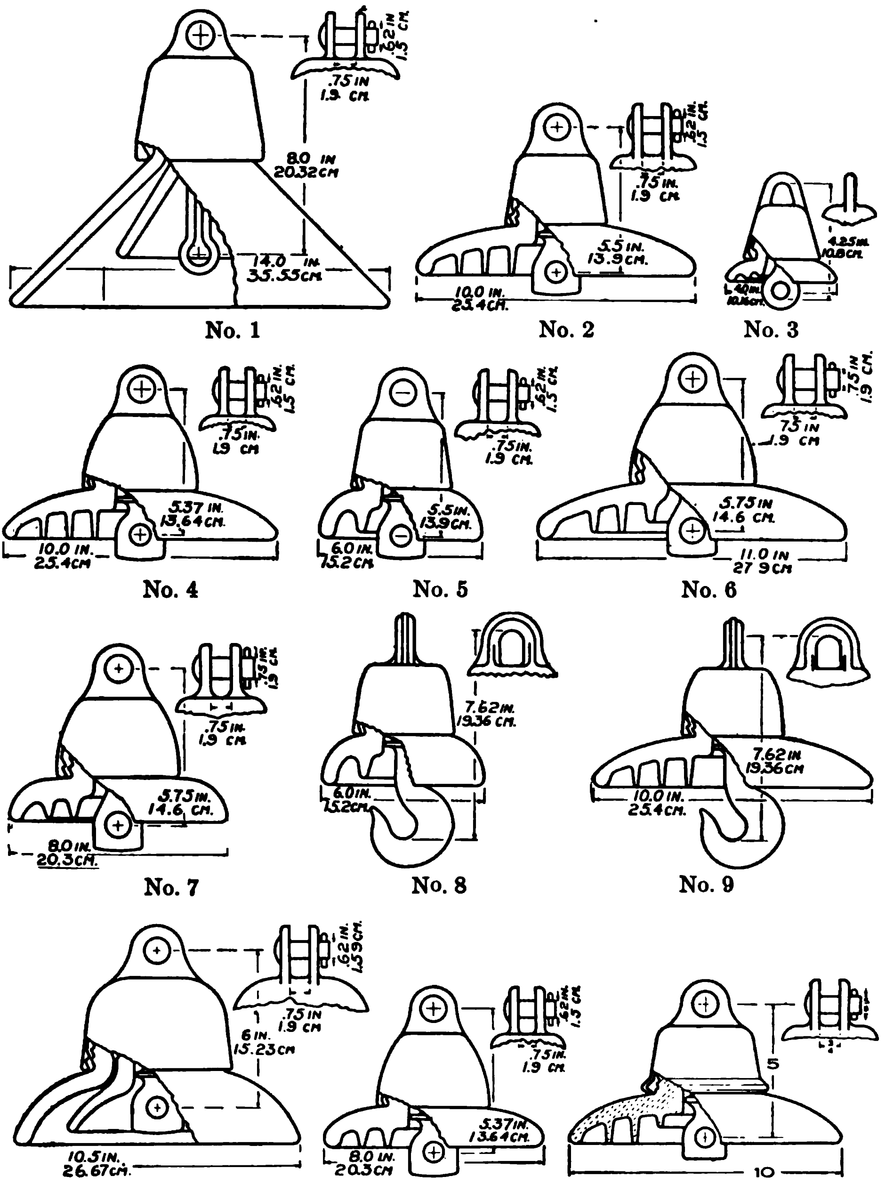


Fig. 111.—Types of Pin Insulators for Transmission Line Voltages around 22,000, 35,000, 45,000, and 75,000 Volts (R. Thomas and Sons Company)

Suspension insulators have a smaller capacity than the multi-part insulator, this capacity diminishing as each unit is added, but increasing for the large sizes of multi-part for higher line pressures. However, a wide multi-part insulator gives better rain protections than the narrower but larger suspension group, yet the number of dry surfaces of the latter gives a smaller surface leakage loss.

Glass Insulators.—The following information on glass insulators for high tension work is abstracted from a paper read at a meeting of the American Institute of Electrical Engineers:

"Glass was the first material to be used for insulators on transmission lines in the United States, and it has shared with porcelain, this application. In France glass is extensively used for transmission lines, we understand, up to 100,000 volts, while in Italy many power lines are similarly equipped. There are 5,000,000 glass insulators giving good satisfaction over high tension lines today in the United States.



No. 1 No. 2 No. 3

No. 4 No. 5 No. 6

No. 7 No. 8 No. 9

No. 10 No. 11 No. 12

Fig. 112a.—Different Types of Suspension Insulators (Locke Insulator Mfg. Co). For Specifications see Table 24

"The problems involved in design and in manufacturing are those of material and of construction. Fundamentally, glass is superior because, being of homogeneous character and a single material, the entire body of the glass acts uniformly as the insulating medium, whereas in porcelain the glaze appears to be the main factor of insulation resistance and differs in composition from the body of the substance which is far inferior to glass in this respect. Now, when it is recalled that this glaze may be but a thousandth of an inch or so in thickness, it is obvious that any imperfections or unevenness in its texture are sure to be fraught with danger. This is further emphasized by recent improvements in glass manufacture which result today in a material, uniform in character, of greater strength and specific gravity, where increased mechanical efficiency and strength are combined with the desired insulating properties. This improvement has followed technical developments in glass making just as in steel and other industries, and is due primarily to a better understanding of the chemical and physical questions involved."

Table 24.—Specifications for a Number of Different Sizes and Types of Suspension Insulators (Locke Insulator Mfg. Co.)

Insulator No. (See Fig. 112a)		1	2	3	4	5	6	7	8	9	10	11	12
Line Voltage KV.	1 unit	30	16	4.4	16	10	16	13	10	16	25	13	16
	2	66	33	..	33	20	33	27	20	33	50	27	33
	3	88	45	..	45	33	45	40	33	45	70	40	45
	4	110	66	..	66	45	66	55	45	66	90	55	66
	5	130	88	..	88	55	88	66	55	88	110	66	88
	6	150	110	..	110	66	110	80	66	110	130	80	110
	7	..	125	..	125	80	125	93	80	125	150	93	125
	8	..	140	..	140	..	140	105	90	140	170	105	140
Dry Arc-over Voltage KV.	1 unit	120	90	50	90	63	90	75	60	88	96	78	90
	2	200	160	..	160	110	160	140	120	160	158	130	160
	3	275	225	..	225	160	225	205	170	240	220	185	225
	4	350	275	..	275	210	275	260	220	320	280	240	275
	5	425	325	..	325	260	325	310	275	400	340	295	325
	6	500	375	..	375	310	375	360	330	480	400	350	375
	7	..	425	..	425	360	425	410	385	..	460	400	425
	8	..	475	..	475	410	475	460	..	..	..	..	475
Wet Arc-over Voltage KV.	1 unit	80	70	20	70	40	70	55	35	60	70	55	70
	2	150	110	..	110	60	110	90	55	95	115	90	110
	3	210	160	..	160	80	160	130	75	130	165	130	160
	4	270	210	..	210	100	210	170	95	180	215	170	210
	5	330	260	..	260	120	260	210	115	225	270	210	260
	6	390	310	..	310	..	310	250	..	270	325	250	310
	7	450	360	..	360	..	360	290	..	315	380	290	360
	8	510	410	..	410	..	410	330	..	360	435	330	410
Leakage distance inches		24	13.5	3.25	13.5	6	13.5	7.75	6	13.5	13.5	8	12
Mech. strength, lbs.		9000	8500	4000	11000	8500	16000	16000	8500	8500	10000	12000	8500
Safe. Max. load, lbs.		3000	2800	1200	4000	2800	6000	6000	2800	2800	3750	4000	2800

The arc-over voltages given above are for insulators without horns. Wet arc-over voltages are given for vertical strings. For horizontal, or strain, position the voltages are approximately 10 per cent. less.

"Unfortunately, glass manufacturers in the United States have failed to realize adequately the availability of their product for high tension work. In the first place, for the new and unusual shapes required, they at first demanded prices that, if not prohibitive, plainly suggested large profits. Secondly, the manufacturers failed to consider sufficiently the electrical side of the problem and did not show a progressive spirit in arranging testing plants and methods of test and experiment. Furthermore, such concerns as have developed improved methods of manufacture, have failed to publish the results of their improvements so that to many engineers, the merits and relative economy of glass as compared with other materials, have never been made apparent. For these reasons chiefly, porcelain has achieved a position in this field which modern glass insulators are now in a position to dispute.

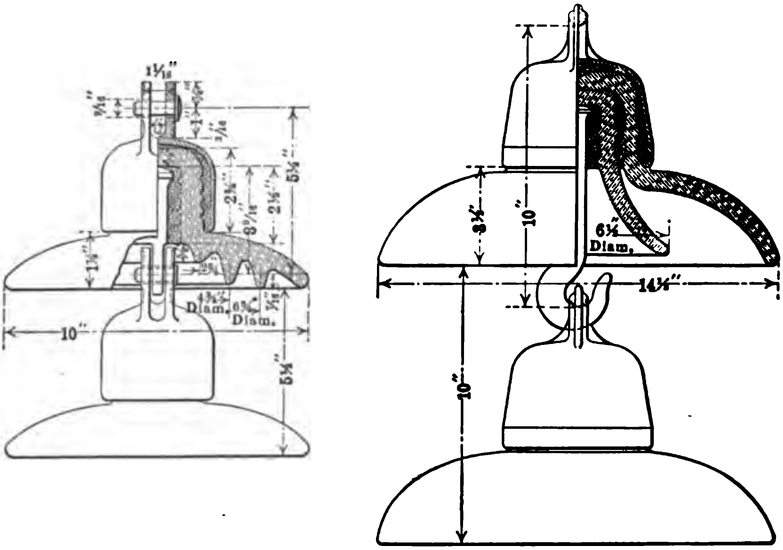


Fig. 112b.—Suspension Insulators for 80,000 to 110,000 Volts (R. Thomas and Sons Company)

The insulator shown at the left for 80,000 volts has been used on the systems of the Alabama Power Company and the Carolina Light and Power Company. The insulator shown at the right for 110,000 volts has been used on lines of the Southern Power Company and those of the Georgia Railway and Power Company.

"In the same way that the different problems of a high tension insulator were solved in porcelain by the suspension insulator, so similar designs have been developed for glass which are now gaining wide vogue. It will be remembered that a porcelain pin insulator required for a 100,000 volt transmission line could be built only of such size and form as to cost, in the average case, a prohibitive amount, but that by combining a number of insulators by cementing to malleable iron fittings and suspending the cable, high tension insulators of such capacity can be secured at a cost of about five or six dollars.

"Likewise in glass units, the suspension insulator is being developed for high tension lines and types now in use meet all conditions in a most satisfactory manner and often more advantageously than porcelain. Instead of making the glass about three inches thick, as has to be done with a pin type insulator where stresses are almost unavoidable, the same result can be secured with glass ¾ of an inch thick. This permits of perfect annealing and the development of a glass with practically the same strength as porcelain. In such discs corrugations of the necessary shape can be molded so that the cement holding the various segments together will have a firm hold and afford an insulator of equal strength to a solid piece."

Today these composite insulators of glass and material called "Boro-Silica" have been developed to a point that suspension insulators are supplied for comparative tests with those of porcelain, irrespective of the voltage for which the line is to be used. For long distance telephone communications, comparative tests have been made of glass insulators and those of other materials along parallel lines, and the practical results as shown in more distinct conversation, have coincided with the reports from the testing laboratory, while the power lines on the Pacific Coast where glass has been used return satisfactory reports. One objection to glass insulators has been that they could only be used with wooden pins. The more perfectly annealed glass insulators have been used with iron pins dipped in pitch and stand up as well as the porcelain. Another objection has been that internal stresses are caused in the piece due to poor annealing. This has been eliminated by a flash-over test of say five minutes and by the more perfect methods of annealing.

Limits of Pin Type Insulators.—An important reason for using suspension insulators is the matter of cost. It is entirely possible to build porcelain insulators of the pin type in standard design of sufficient size to operate successfully at any voltage, but the extreme height and diameter of a pin type insulator for, say, 100,000 volts make the cost prohibitive. Suspension insulators are usually made up on the unit plan, making it possible to increase the effective insulation whenever it is desired to raise the line voltage or whenever it is found necessary to increase the leakage surface of the insulators in districts where salt fogs or dust deposits from factories are encountered. Many lines start operation at a lower voltage than will be eventually used because the initial load is light and the potential increased when the regulation demands it. If the pin type of insulator is considered at the start in such a case, there is no choice but to install the size of insulator that will be ultimately required. Again in the pin type of design, the nearness of the line wire and pin must always prove a weak point for lightning as well as any surging or other line disturbances. The suspension type of insulator gets around both these troubles by the wide separation of the conductors and supporting structure. Again when the suspension type is used on towers, the position of the conductor below the cross-arm permits the tower to act as a lightning rod, and relieve the line from much lightning stress.

Insulators are a source of much line trouble and in the matter of breakage the unit suspension type has a positive advantage. When a pin type insulator becomes cracked the whole insulator is worthless so far as its electrical properties go, and must be removed at once or it may cause a shut-down during the first rain storm. The breaking or cracking of one of the units of a suspension unit type insulator takes away but one unit of the series. Thus, in a five-unit design for 100,000 volts, the breaking of one unit reduces the insulating value only 20 per cent. The suspension insulator requires a higher tower and pole for the same wire clearance than when using the pin type design, for the conductor is below the cross-arm and a longer cross-arm is also required to allow for the swing of insulators and wires in the wind.

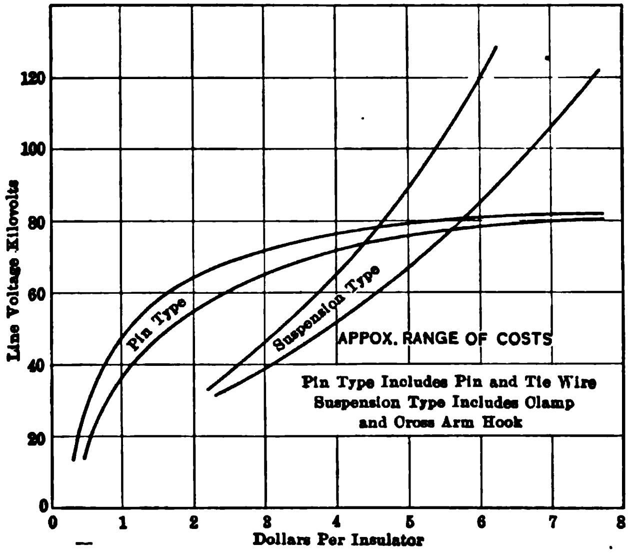


Fig. 113.—Comparative Insulator Costs (Locke Insulator Mfg. Company)

For pin type insulators the costs include tie wire and pin and for the suspension type the cross-arm attachment and clamps. The maximum cost represent liberal safety factors such as steel pins and liberal pin type insulator rating and in the case of suspension insulators, most substantial clamps, attachments and two-piece suspension insulators. The minimum costs represent closer insulator rating, wood pins, etc.

On account of these features, a construction dealing with voltages above 50,000 is now considered about the dividing line between pin type and suspension type insulators, with a suspension type often used on lower voltages where there is the possibility of increasing the voltage of the line in the future, as already mentioned.

Insulator Costs.—The curves of Fig. 113 show the relative approximate cost per insulator of the pin and suspension types. The maximum costs represent liberal safety factors, such as steel pins, liberal pin type insulator rating, substantial clamps, attachments and two-piece suspension insulators. The minimum costs are for close insulator ratings, wood pins and the like. Inasmuch as the insulator is one of the important factors in uninterrupted service and line maintenance, and represents a relatively small part of line cost, it is essential that liberal design be allowed in its selection.

Insulator Grounds.—Choice of transformer and system connections still continue to raise differences of opinion. Before the successful development of the electrolytic lightning arrester the advantage was on the side of the star transformer connection with neutral grounded. Between the delta connection with 50 per cent. of the line potential on the insulators and the star connection with 60 per cent. there is little choice. In the case of the delta connection, a broken insulator does not result in a short circuit, but the grounding may set up severe high frequency disturbances, with the entire line voltage on the remaining insulators. This danger is lessened as the line voltage increases. When arc suppressors are used such arcing grounds are immediately disrupted by short circuiting. On the other hand a broken insulator on a star grounded system must be replaced at once. In this connection the voltage on the insulator is fixed whereas with the delta connection the limiting voltage is determined by the arrester setting within its range. The isolation of the delta with reference to the ground potential permits of extreme super-voltages and surging unless limited by arresters or other means.

Insulator Troubles.—Formerly a large number of insulators were broken supposedly by hunters using them as targets and boys throwing stones at them. On narrow spacing of conductors insulators have also been lost from large birds short circuiting the line. Fog and dust undoubtedly are the greatest sources of present troubles, however, aside from electrical disturbances. Fog decreases the surface resistance of the insulator so that there is sufficient leakage to burn wood cross-arms and pins. Trouble from fog alone can usually be remedied by larger insulators except in the case of salt fog or fog and dust or smoke. Salt fog causes an encrusting of the surface of the insulator which can only be remedied by periodic washing. In districts where the air is laden with cement dust, smoke or acid fumes, fog adds to the regular run of insulator troubles with the remedy largely an increase in size of insulator and dependence on rain to maintain the insulator in working condition. Insulators have been designed and are available which protect inner petticoats from fog and dust and also relieve this trouble. Insulator troubles from electrical disturbances, mainly from lightning, show up as broken units from puncture, porcelain cracked, or chipped, corrosion of the pin due to improper cementing and the like. These defects can be usually located by the ordinary 1,000 volt megger test or by a telephone receiver test which is being used successfully by several large companies. A 2,000 ohm wireless receiver set is used with one terminal connected to a spike about shoulder high above the ground and the other terminal to another spike driven in the ground a few feet from the base of the pole. If the insulator is defective there will be distinct scratching noise in the receiver. The particular unit is then found by climbing the pole and testing the insulator units separately. An exploring coil and telephone receiver is employed by one company with considerable success.

Insulators fail electrically through actual puncture or by flash-over and cracking. The first cause of failure can be practically eliminated by tests applied before the insulator is placed in service to weed out the weak units. Flash-over tests are less satisfactory as an indication of what the insulator is likely to do in the long run. In the first place it is very difficult to imitate the insidious coating of the surface by the long continued action of dust and moisture. Almost any first class porcelain will withstand admirably a puncture test or a flash-over test dry, the limitation being the size and design of the petticoats. The value of a flash-over test when the insulator is wet depends upon the nature of the wetting. The ordinary spray test approximates a heavy but rather quiet shower of rain. Service conditions would be more nearly approximated by a very fine spray directed obliquely upon an insulator which had previously been coated with fine dust.

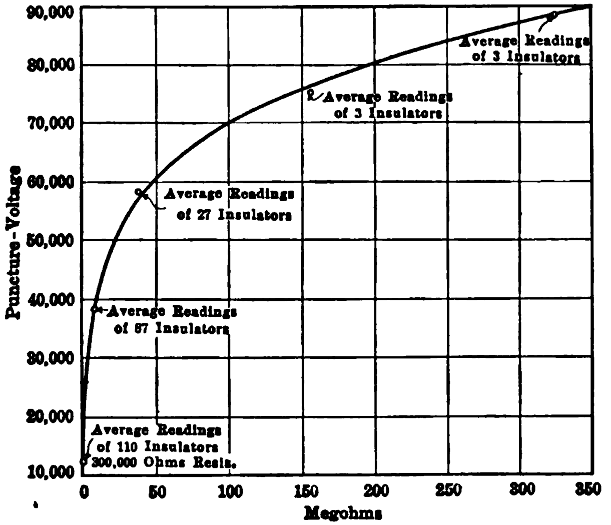


Fig. 114.—Relation between Megohms and Puncture Voltage for 230 Insulators Taken from the Baltimore Transmission Line of Pennsylvania Water and Power Company

Testing Insulators with Megger.—In comparing the resistance of suspension types of insulators, as determined by a megger, with the puncture voltage, the Pennsylvania Water and Power Company has found that the latter increases in a general way with the resistance. In fact, the ratio of puncture voltage to resistance followed very closely the curve of Fig. 114. Units having a resistance of about 50 megohms had a puncture value about

60,000 volts, while those having a resistance of 350 megohms had a puncture voltage close to the flash-over value. It seems advisable, therefore, not to allow insulators to remain in service on a 70,000 volt line unless each unit has a resistance of at least 500 megohms.

Flash-over of Suspension Insulators in String.—Interesting observations have also been made by this company on two 70,000 volt lines both equipped with the same design of suspension insulators, the one line with five units to the string in suspension and six units on strain towers, the other line with seven units to the string in suspension and eight in strain. Records for one year for both lines showed the larger number of lightning strokes for the line with the larger number of insulators. Evidence from inspection of the line showed, however, that whenever the flash-over took place on a suspension tower (which generally was the case in preference to a strain tower) the lightning arc on the circuit with the five insulators in the string, would as usual rise upwards along the insulator strings to the crossarm above, while on the circuit with the seven units in the string the arc would in every case go just the opposite way, that is, from the conductor to the crossarm below, as shown in Fig. 115. This was naturally due to the fact that this clearance distance for the two upper conductors was materially decreased (from about 36 in. to 24 in.) by adding two more units to the string. For the bottom conductor, where the clearance distance still remained ample, the number of flash-overs was greatly reduced. This change in the location of the arc resulted in two distinct gains. In the first place, the arc did not have nearly the same chance for damaging the insulators by heat, as it did not pass alongside them but away from them. The insulator record for 1913 showed this clearly. Thus it was necessary to remove 210 insulators from circuit No. 2, (Fig. 115) due to lightning damage, and only three from No. 1 circuit. The other advantage gained was that it proved to be easier to extinguish the arcs on No. 1 circuit and that it could be done with much less loss of the synchronous load connected to the system, on account of the preponderance of two-wire short circuits compared with three-wire short circuits. The following year one more unit was added to No. 2 circuit suspension towers and two more to the strain towers, and this is the way it is at present. The number of insulators removed from the line due to lightning damage is small, not more than about one hundred per year, on the average, and is not on the increase.

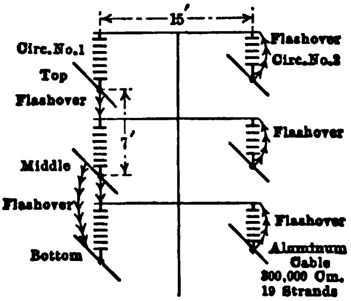


Fig. 115.—Different Paths Taken by Lightning Flashovers

Puncture and Flash-over Ratio for Insulators.—There has been some difference of opinion among operating engineers and insulator designers as to the proper relationship between puncture voltage and flash-over voltage. It is usually considered that a proper ratio of puncture voltage to flash-over is about 2 to 1. Some engineers hold, however, that an insulator of very large striking distance may have a comparatively low flash-over voltage and may easily have a dielectric strength as based on oil tests of 2 to 1, yet as far as operating conditions go, such an insulator may not be nearly as good as one of some other ratio, because of the fact that the latter may have a shorter striking distance.

In the National Electrical Safety Code issued as Circular No. 54 by the Bureau of Standards, November 15, 1916, in the section on installation and maintenance of lines, it is recommended that insulators be so designed that their dry flash-over voltage is not more than 75 per cent. of the puncture voltage at a frequency of 60 cycles. It is also recommended that insulators withstand without flash at 60 cycles a test voltage when dry from 4 to 2.5 times the operating voltage and when wet from 3 to 1.5 times the operating voltage. The test voltages of 4 and 3 times operating voltage were given for 6,600 volt insulators and the values 2.5 and 1.5 for 150,000 volt insulators. The test voltages between these sizes and ratings are given in a table in the last chapter of this book devoted to data and reference tables.

Hot and Cold Water and Vacuum Heating Tests for Insulators.—A hot and cold water test for insulators is often employed to determine the types of insulators that are most liable to be damaged by high internal stresses. Results of such tests as conducted and formulated by the Pennsylvania Water and Power Company, ("Proceedings A. I. E. E.," July, 1915) have led to certain practical conclusions which are of value in interpreting high-voltage tests. In the tests as conducted by this company, the heads of the insulators were dipped in cold water (7 deg. to 8.5 deg. C) for five minutes, then immersed in boiling water for an equal period, and finally tested for resistance with a megger. Those which stood the treatment without any change in resistance were subjected to ten temperature changes and finally to a high-voltage test.

By heating insulators which had been in service on the line for some time in a vacuum to a temperature of 50 deg. to 90 deg. C., it was found that the resistance gradually decreased and after several days rose again to infinity. When insulators which had been subjected to this treatment were subjected to high-voltage tests, it was found that they would break down at a much higher voltage than before being treated. The insulators which dried out the quickest punctured at the lowest voltages while those that dried out more slowly had considerably higher break-down values. From these observations it seems that insulators which have become unsuitable for service owing to absorption of moisture can be made safe for service by heating them in a vacuum and treating them so they will not absorb moisture again. Switching, surges, arcing grounds, high-frequency discharges, etc., therefore, can hardly be assumed to be the cause of all insulator depreciation, since insulators have been damaged on lines continuously energized but not used to transmit energy.

Effect of Altitude on Insulator Ratings.—F. W. Peek, Jr., has shown* that there is a considerable variation of the spark-over voltage at sea level and at high altitudes for insulators, bushings and leads. If the spark over-voltage is known at the sea-level the spark-over voltage at any altitude may be closely estimated by multiplying by the corresponding relative air density (ratio at sea level to that at any other altitude). That is, if a suspension insulator string of three units has a spark-over voltage of 205,000 volts at sea level, the spark-over voltage at 9,000 ft. elevation at the same temperature would be, $E=0.71\times 205{,}000=145{,}000$ volts, where 0.71 is the relative air density corresponding to 9,000 ft. elevation.

Protective Apparatus.—On account of the fact that abnormal and transient disturbances frequently arise during the operation of transmission lines against which it is beyond practical methods to insulate apparatus, certain types of protective apparatus are essential. The protective devices in common use include lightning arresters, reactance coils, automatic circuit breakers, relays, arcing ground suppressors, overhead ground wires and the like. The abnormal conditions that may injure machines and cause interruption to service, include:

1. High frequencies.
2. Abnormal voltages.
3. Excessive currents.
4. Improper switching and accidental conditions.

Lightning is the most troublesome cause of high frequency oscillations, while the arcing ground and changes in electromagnetic or electrostatic conditions also cause oscillations. Abnormal voltages are also the result of lightning, resonance and the reflection of standing waves and frequently rupture insulation or strain it to a point where it will eventually fail. Excessive current is about as serious as the other two abnormal conditions on account of the damage to insulation through overheating. Improper switching and its effects are treated under this head in the section on system connections. The accidental conditions referred to as sources of abnormal disturbances are such accidents as breaks in conductors due to storms and failures due to faulty installation and construction of insulators, switches and the like.

Electrolytic Lightning Arrester.—The essential features of the electrolytic lightning arrester are shown in Fig. 116. This device has proved most effective in protecting alternating current systems and apparatus from all potential surges and lightning disturbances and is now generally used in all cases where the service and apparatus to be protected will justify the expense. The construction and operation of the electrolytic arrester are based upon the characteristics of the aluminum cell consisting of two aluminum plates on which has been formed a film of hydroxide of aluminum immersed in a suitable electrolyte. The device has a large discharge capacity and will not only handle serious abnormal conditions caused by lightning, but will as well handle both continuous and recurrent discharges lasting for long periods. This arrester can be adjusted to discharge at only a small percentage above the normal operating voltage of the system. The arrester should be installed as near the apparatus it protects as possible and for this reason it is built in indoor and outdoor designs. Indoor units are used for low voltages where the arcing at the horn gaps is not severe under even abnormal cases. Above 27,000 volts, however, the arrester tanks are installed inside and the horn gaps installed just outside the building so that the leads can be connected to the line where it enters the station.

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* Dielectric Phenomena in High Voltage Engineering, McGraw-Hill Book Company, New York, page 111.

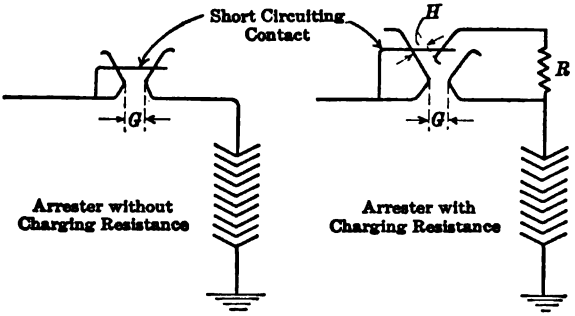
Short Circuiting Contact
H
R
G
G
Arrester without Charging Resistance
Arrester with Charging Resistance

Fig. 116.—Horn Gaps and Short Circuiting Contacts for Electrolytic Lightning Arresters. Short Circuiting Device should be Set (G+25%) from Opposite Horn

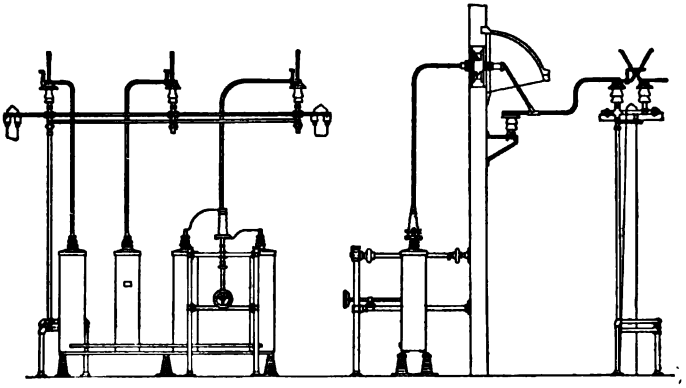

Fig. 117.—Lightning Arrester Installation for 45,000 Volt Three-Phase Non-Grounded Neutral System, Showing Horn Gaps on Wooden Poles, Wall Entrances and Tanks Inside of Station (General Electric Company)

Such an installation is shown in Fig. 117. The objection to installing arrester tanks out of doors comes from the liability of freezing in winter and exposure to the sun in summer. When the electrolyte is frozen the internal resistance of the arrester is considerably increased and its discharge rate considerably lowered. A high operating temperature increases the rate of dissolution of the films which calls for more frequent charging. In very hot climates it may be found advisable to charge two or more times a day, since failure to keep the film in proper condition at high temperatures increases the liability of damage from a heavy charging current.

Arresters for Grounded and Non-grounded Circuits.—It has been pointed out by R. T. Wagner (*General Electric Review*, June, 1913) and others, that it is important to avoid the mistake of selecting an arrester for a thoroughly grounded neutral when the neutral is only partially grounded, that is, through an appreciable resistance. In an arrester for a grounded neutral circuit, each stack of cones normally receives the neutral potential when the arrester discharges. But if a phase becomes accidentally grounded the line voltage is thrown across each of the other stacks of cones until the circuit breaker opens the circuit. The line voltage is 173 per cent. of the neutral or normal operating voltage of the cells and therefore about 150 per cent. of the permanent critical voltage of each cell. This means that when the grounded phase occurs this 50 per cent. excess dynamic potential is short circuited through the cells until the circuit breaker opens. The amount of energy to be dissipated in the arrester depends upon the kilowatt capacity of the generator, the internal resistance of the cells and the time required to operate the circuit breakers. The greater the amount of resistance in the neutral the longer will be the time for the circuit breakers to open. In all cases, therefore, when the earthing resistance in the neutral is great enough to prevent the automatic circuit breakers from opening practically instantaneously, an arrester for a non-grounded neutral system should be installed. General Electric arresters for circuits with thoroughly grounded neutrals have three stacks of cones. The bases of the stacks of cones are connected to the tanks and grounded. The top cone of each stack is connected to the line through a horn gap. Insulating supporting racks are not necessary with arresters for grounded neutral circuits. For non-grounded circuits the arresters have four stacks of cones, the bases of which are connected together by a multiplex connection. The fourth stack is between the multiplex connection and the ground, the object being to give the same protection between the line and line as between the line and ground. The fourth stack is called the grounded leg of the arrester.

Installation of Arresters.—When installing an arrester it is important that the wiring of the discharge circuit should furnish the shortest and most direct path from line to ground. Copper tubing is recommended for high voltage arresters installed with large radius bends and as short length of conductor as possible so as to eliminate unnecessary inductance and enable the arrester to properly handle high frequency disturbances. From the arrester to ground copper strip is sometimes more convenient to install than copper tubing for this can be fastened to the station wall and lead directly to the ground. It is important to secure a good ground connection and a plan better than the use of ground plate is to connect to several pipes driven six to eight feet in the ground and widely separated, but connected together with a liberal size of copper conductor. When plates are used at a distance from the arrester, as in the mud bank of a stream, a pipe should be driven in the ground near the arrester to make the ground connection as short as possible. Ground plates at a long distance are not satisfactory. It is advisable to measure the resistance of ground connections from time to time. According to R. T. Wagner in the *General Electric Review*, February, 1913, the resistance of a single pipe ground can be considered good when about 15 ohms. A simple method of checking up the condition of multiple pipe grounds is to divide the pipes into two groups and connect each group to a 110 volt lightning circuit with an ammeter

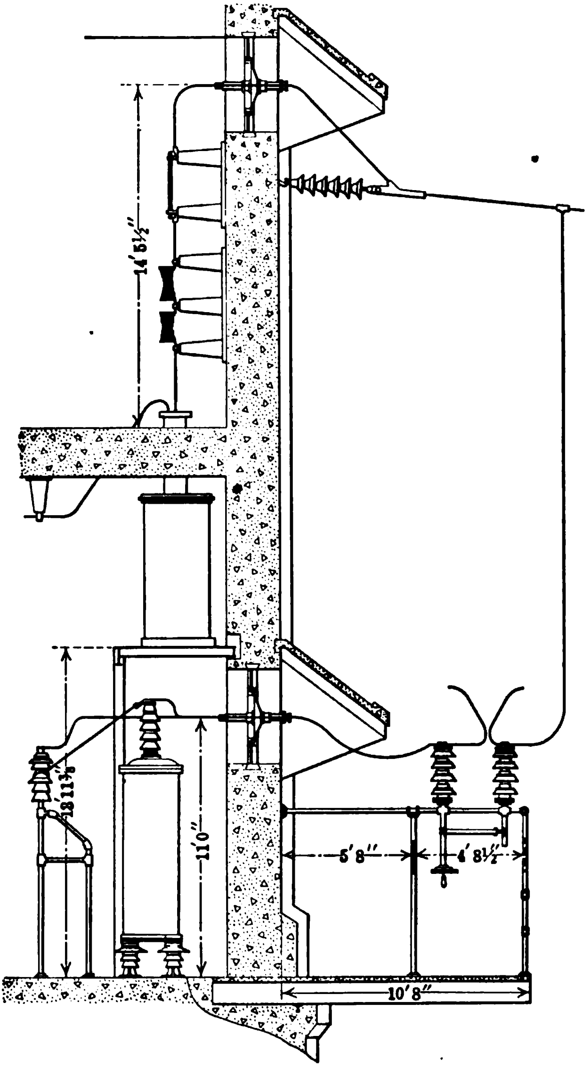

Fig. 118.—Transformer House Showing Outgoing Line and Lightning Arrester Connections

in series. If about 20 amp. flows and the pipes are well distributed the ground conditions are satisfactory for lightning arresters.

Resistance of Grounds.—The data in Table 25 give the resistance of various ground connections under similar conditions. The results were secured from a number of types of ground connections installed at 10-ft. intervals. After allowing these to settle for a period of three months, measurements were taken every three months for a period of eighteen months over a wide range of temperature and moisture conditions. The resistance of any one type varied very little under any weather conditions, the maximum variation of any reading being 35 per cent. of the average value.

Table 25.—Resistance of Different Types of Ground Connections

No.	Description	Ohms
1	10 lb. scrap copper set 6 ft. deep, surrounded by 10 lb. coke	14.2
2	Copper plate, 5 ft. by 3½ ft., set 4 ft. deep, surrounded by 2 ft. crushed coke	5.6
3	One 9-ft. length 1¼-in. black iron pipe driven 6 ft. in solid earth	25.1
4	One 9-ft. length 1¼-in. galvanized-iron pipe driven 6 ft. in solid earth	24.5
5	One 12-ft. length 1¼-in. black iron pipe driven 9 ft. in solid earth	14.8
6	One 12-ft. length 1¼-in. galvanized-iron pipe driven 9-ft. in solid earth	18.4
7	Two 9-ft. lengths ¾-in. galvanized-iron pipe set 6 ft. deep and coke tamped around pipes	15.2
8	One 9-ft. length 1¼-in. galvanized-iron pipe set 6 ft. deep and coke tamped around pipe	26.7
9	Perforated metal cone 18 in. long, filled with charcoal, buried 6 ft. in 2 ft. of coke	14.4
10	Patented type of driven ground pipe	19.5
11	Patented type of set ground connection	11.7
12	Connection to city water system at faucet placed about 100 ft. from test grounds	00.44

Rating of Lightning Arrester.—The voltage ratings of electrolytic lightning arresters are given in column one of Table 26a, together with the minimum and maximum voltages at which they should be operated. All arresters on a system should be capable of operating at the generating station voltage. Manufacturers report that a mistake is often made in specifying an arrester of lower voltage for a substation than for the generating station allowing for the line drop. Disastrous results often follow such an error since the generating station voltage may be thrown on the substation arresters when the load is light or is suddenly cut off the substation.

Arrester Horn Gap Settings.—The gap settings in the accompanying table are for the main and resistance horn gaps as recommended by the General Electric Company. When arresters are operated at higher or lower voltages than given in the table larger or smaller settings corresponding to the operating voltage should be used. In case arresters are used with charging resistances, the resistance gap should always be slightly smaller than the main gap in order to give a selective path for the discharges. The variations should be about as shown in the table.

TABLE 26a.—VOLTAGE RATINGS AND LIMITS OF ELECTROLYTIC ARRESTERS

RATED VOLTAGE	OPERATING VOLTAGE	
	Minimum	Maximum
2500	1000	2550
3300	2551	2600
4600	3601	4680
6600	4681	7250
10000	7251	11900
12500	11901	14000
15000	14001	16100
17500	16101	18700
20000	18701	21800
25000	21801	27000
30000	27001	32200
35000	32201	37900
40000	37901	43000
45000	43001	48250
50000	48251	53500
60000	53501	64250
70000	64251	75000
90000	75001	95000
110000	95001	115000
140000	115001	145000

Recommendations by R. T. Wagner, *General Electric Review*, February, 1913.

TABLE 26b.—GAP SETTINGS IN INCHES FOR ARRESTERS WITH AND WITHOUT CHARGING RESISTANCE

ARRESTER VOLTAGE	MAIN GAP		RESISTANCE GAP	
	Max.	Min.	Max.	Min.
2500	3/32	3/64	1/16	1/32
3300	1/8	5/64	3/32	1/16
4600	3/16	1/8	5/32	3/32
6600	5/16	7/32	1/4	5/32
10000	3/8	1/4	5/16	3/16
12500	7/16	5/16	3/8	1/4
15000	9/16	3/8	15/32	5/16
17500	11/16	7/16	9/16	3/8
20000	3/4	1/2	5/8	7/16
25000	1.00	11/16	13/16	9/16
30000	1 1/4	7/8	1 1/8	3/4
35000	1 5/8	1 1/8	1 1/2	1.0
40000	2 1/8	1 3/8	1 7/8	1 1/4
45000	2 5/8	1 3/4	2 3/8	1 1/2
50000	3 1/4	2 1/8	3	1 7/8
60000	4 1/2	3	4	2 3/4
70000	6	4	5 1/2	3 1/2
80000	8	5 1/4	..	..
90000	10	6 3/4	..	..
100000	12 1/2	8 1/2	..	..
110000	14	10	..	..
140000	18	13	..	..

Recommendations by R. T. Wagner, *General Electric Review*, February, 1913.

Other Forms of Arresters.—Other forms of arresters such as the multigap, horn gap, magnetic blowout and mechanical break designs are in use where the conditions are less severe than in connection with long transmission lines serving substation and important customers and where the operating conditions require a less expensive protective device than the electrolytic arrester.

Protective reactance coils or choke coils are used to limit power to safe values at times of short circuit and to absorb and reflect high frequency oscillations by virtue of their inductance and resistance. They are also used as retardation coils with electrolytic lightning arresters. Coils of from 20 to 40 turns air insulated are usually satisfactory for this purpose. They are installed in series with the line, preferably just outside a station between the apparatus and the lightning arresters.

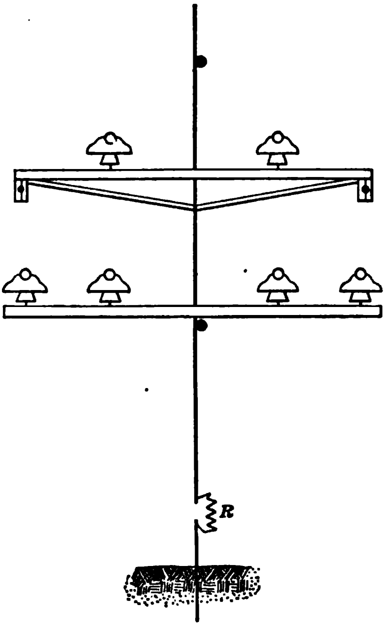

Fig. 119.—Position of Four Ground Wires when Non-Grounded Pins are Used

Overhead Ground Wires. — The value of the overhead ground wire is being realized more and more and the opinion held that the more of them the better the protection to lines against electrical and magnetic disturbances during lightning storms.* The most practical protection is secured from four grounded parallel wires in a rectangular formation which gives the widest separation. These may be placed two above and two below the power conductors, or two above and one each side about on a level with the two lowest power conductors. Where a single ground wire is used it should be placed as near as practicable to the power conductors. When two grounded wires are used they should be separated as far apart as possible and as far as practicable should be on opposite sides of the power conductors. This will reduce to a minimum the transfer of surge energy to the power conductors. Protection against the splitting of poles may be secured by vertical conductor which runs the height of the pole and has one end buried in the ground. Every fifth pole protected in this way serves as a protection from a direct bolt of lightning. A position of four ground wires recommended by Dr. E. E. F. Creighton where non-grounded pins are used is shown in Fig. 119. To preserve the insulation afforded by the wooden cross arm the metallic connections of the laterally grounded wires are carried free of the cross arm. At one point in the circuit is shown a series resistance to bring the total resistance in the grounded loop up to a value at least equal to one-fifth of the critical damping resistance.

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* "Theory of Parallel Grounded Wires and Production of High Frequencies in Transmission Lines," by E. E. F. Creighton, "A. I. E. E. Proceedings," June, 1916.

Size of Ground Wire.—From a mechanical standpoint the size of ground wire is dictated by the length of the span. To guard against sleet, practice seems to call for a ⅜ in. stranded Siemens-Martin steel wire for a span of 600 feet and ¼ in. for a span of about 250 feet and ordinary telegraph wire for spans of about 100 feet. The distance between the ground wire and the nearest conductor at the point of support should not be less than 70 per cent. of that allowed between the conductors, assuming that the ground wire is of steel and the conductors of copper or aluminum. When the ground wire is of the same material as conductors the same minimum clearances apply to it.

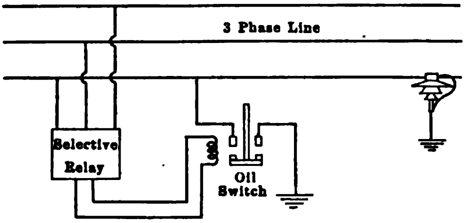

Fig. 120.—Essential Features of Arcing Ground Suppressor

With average cost of steel wire and cost of stringing the ⅜ in. ground wire will cost around $100 per mile. Each overhead ground wire can be considered roughly as from 5 per cent. to 1.0 per cent. of the cost of the line when its total cost, including steel towers, is considered from $2,000 to $12,000 per mile.

Arcing Ground Suppressor.—Where a system is operated without grounded neutral interruptions to service have been successfully prevented from arcing grounds by use of the arcing ground suppressor. This device in the main consists of three single-pole independent motor-operated oil switches electrically and mechanically interlocked to prevent more than one operating at the same time. It is controlled by a balanced three-phase potential relay which remains inactive while the system is balanced, but when unbalanced due to the ground on one phase, it operates the corresponding phase of the suppressor which in turn grounds the same phase of the line, thus shunting the current and extinguishing the arc. Its action and effect on a transmission system was explained by Creighton and Whittlesey in "A. I. E. E. Proceedings" of June, 1912.

Arcing Horns and Rings.—These devices are sometimes used on insulators with the idea of forming terminals to take the craters of an arc in case of insulator flashover. It is thought that a large percentage of insulators reported destroyed by puncture are first cracked or broken by the heat of an arc allowing current to flow through the break and blow up the insulator.

The arcs may be due to lightning or disturbances in switching and against them it is not practicable to insulate. The arcing rings and horns such as shown in Fig. 121 limit the voltage of the destructive discharges over the insulator. The advantage of the ring design lies in the fact that the arc can form at any point around the insulator and in case it forms on the windward side it may be blown around without injury to the insulator whereas with definite terminals the arc may be blown under the insulator and injure it.

TABLE 27.—ADJUSTMENTS FOR ARCING HORNS (LOCKE INSULATORS)

The gaps on strain strings and yokes are the same as for suspension strings, for equal number of units in the strings. The arc-over voltages are given in kilovolts and gap length in inches as in Fig. 121.

INSULATOR No. See Fig. 112a	1		2		4		6		7		10		11		12	
	Gap	KV.	Gap	KV.	Gap	KV.	Gap	KV.	Gap	KV.	Gap	KV.	Gap	KV.	Gap	KV.
2 units	9	102	6.5	80	6.5	80	6.75	82	6.75	82	6	76	6.5	80	6	76
3 "	17	177	12.	131	12.	131	12.5	136	12.5	136	12	131	12.	131	11	122
4 "	25	252	17.5	182	17.5	182	18.25	189	18.25	189	18	186	17.5	182	16	168
5 "	33	326	23.	233	23.	233	24.	242	24.	242	24	242	23.	233	21	214
6 "	41	400	28.5	284	28.5	284	29.75	296	29.75	296	30	298	28.5	284	26	261
7 "	49	472	34.	335	34.	335	35.5	350	35.5	350	36	354	34.	335	31	308
8 "	57	545	39.5	386	39.5	386	41.25	405	41.25	405	42	409	39.5	386	36	354

Horn gap spacings for different arrangements and voltages are given in the accompanying table. It must be understood that arcing horns and rings are not a makeshift to use poor insulators—they are simply one form of protection against line surges.

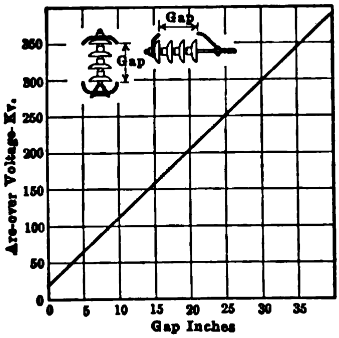

Fig. 121.—Standard Gap Adjustments for Arcing Horn Combinations

Isolating Transformers to Reduce Arcing Ground Disturbances.—On the lines of the Public Service Company of Northern Illinois practical use has been made for some time of the isolating transformer idea on a non-grounded neutral system. The usual plan, as worked out, provides for isolating the system at generating stations or at points where local distributing lines are supplied. As may be observed from the accompanying single line diagram (Fig. 122), this arrangement exists at the Blue Island and Streator stations. The step-up transformer banks normally operate in parallel on the generating bus, but are isolated on the high-tension side. Provision is made, however, for parallel operation on a high-tension bus at Blue Island, or for cutting the line through and by-passing the station at Streator, in case of transformer trouble or other unusual conditions. In this manner the system as a whole operates in parallel but in isolated sections, thus limiting in extent metallic inter-connections and consequent disturbances to restricted areas.

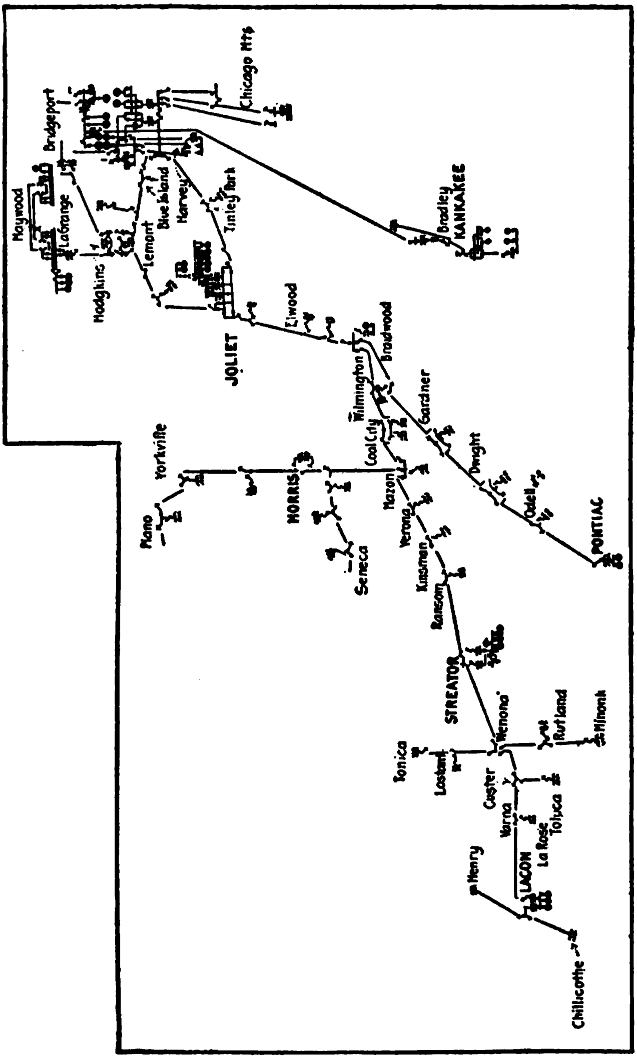

Fig. 122.—Transmission System of Public Service Company of Northern Illinois Showing Isolated Transformer Arrangements at Blue Island and Streator Stations

At the Streator installation, station-type regulators are installed on the low-tension side of the step-up transformer bank, which maintains proper regulation for the intervening points along the line extending to the west.

This appears to be one of the main advantages of the isolating scheme as worked out in the system of high-voltage distribution.

In the case of a metallically inter-connected system, a single defective insulator which grounds a phase affects the entire system. Local storms often develop in one section and cause a hazard to service in every other section. When isolating transformers are installed the disturbance of an accidental arcing ground on one section is confined entirely to that section, and still power may be transmitted without interference to and from all other sections as under normal conditions. Where isolating transformers are installed 1 to 1 units may be used or standard units which step the voltage down and up again to the transmission voltage. Delta connection of transformers is employed.

In the development of high-voltage distribution systems, consisting of an inter-connected network of lines, the necessity of protective devices for localizing high-voltage disturbances becomes more and more apparent as the system is extended. The scheme of adapting the transformer for this purpose is proving to be an effective means in limiting the extent of line disturbances, and unless some protective device is developed which will fulfill the requirements the transformer will be used, but perhaps in a modified form, designed for the conditions imposed.

Grounding vs. Insulating Metal Crossarms on Wood Poles.—The advisability of insulating as opposed to grounding the arms of wood pole lines depends upon whether or not it is advisable to nurse weak insulators and maintain service with grounds on the line. With insulated arms the insulating value of the pole to ground is retained and in case of an insulator failure only the two remaining insulators on the arm in question will be subjected to full line voltage whereas, with grounded arms or metal arms where the ground wire is clamped directly to the bayonet, two-thirds of the insulators on the line will have the full line voltage impressed across them, which is sure to locate any weak units, with a resultant short circuit and interruption of service until repairs are made. The problem is similar to that of grounding the neutral of a star connected system, and in general, it is well to insulate the arms on lines serving important loads with no other source of supply, and to ground the arms in networks or where emergency service is provided. For ungrounded systems better results will be obtained with ungrounded arms. Where the system neutral is grounded the metal cross arm should be earthed.

Protecting Distribution Transformers.—Results of an extensive investigation to improve lightning protection for distribution transformers conducted by the Commonwealth Edison Company* have indicated that considerable trouble from lightning can be eliminated by removing transformer terminal boards and installing lightning arresters on the same poles with the transformers. These conclusions are drawn from a five-years' investigation which included 3000 miles of circuit and 16,000 transformers. The records obtained have demonstrated, first, that the removal of the terminal boards from transformers would eliminate about 60 per cent. of the troubles due to lightning, and, second, that the installation of lightning arresters on the same pole with each transformer made a very considerable additional reduction in the amount of trouble from lightning, as compared with previous practice of installing a few arresters on the line poles. Regardless of whether the lightning arresters are on line poles or on transformer poles, the protection appears to be improved by an increase in the number of arresters per square mile or per mile of line. While a lightning arrester on the same pole with each transformer appears to be quite adequate protection in a region where the transformers are reasonably close together, the protection appears to be inadequate where the transformers are separated by distances greater than 2,000 feet. Construction is considerably simplified by the use of self-contained arresters which do not require inspection. The modern types of lightning arresters are so free from trouble that the installation of a fuse in series with the arrester, for the purpose of disconnecting the arrester in case of trouble, is not warranted. While the installation of lightning arresters for the protection of transformers is not warranted by the saving in the cost of repairs to transformers, it can be justified because the quality of the service is improved thereby.

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* "Studies in Lightning Protection on 4,000 Volt Circuits," by D. W. Roper, "A. I. E. E. Proceedings," June, 1916.

Where transformers are separated by considerable distances, or are located at the end of a long line, the indications are that a single arrester on the transformer pole will prove inadequate. In order to secure the best protection, therefore, a certain minimum distance (not yet determined) between arresters should be decided on so as to protect against the lightning strokes of moderate frequency and considerable volume, which cannot be discharged by a single arrester, and which are apparently a fair proportion of the total number of strokes. Lightning arresters protect transformers against a large fraction of the lightning strokes, but the rest of the strokes, which are probably of a very high frequency and large volume, are beyond the capacity of the arrester. Stated more specifically, some lightning strokes are of comparatively low frequency and moderate volume, so that an arrester placed anywhere along the portion of the line affected by the stroke will protect the transformers. This type of stroke is the only kind that is seriously affected by the old-fashioned scheme of scattering a few arresters along the line poles. For strokes of higher frequency it becomes necessary to have the arresters nearer the transformers, and this may be accomplished in part by installing an arrester on the pole next adjacent to each transformer. For strokes of very high frequency, however, the arrester on the pole next adjacent to the transformer is no longer sufficient, and the arresters must be placed immediately alongside the transformer. There still remain strokes of such high frequency and volume that a single arrester on the transformer poles becomes inadequate on account of its limited discharge capacity. This may account for the damage done to the transformers that are so protected.

CHAPTER V

PLANT, LINE AND SUBSTATION COSTS

Unit Construction Costs for a Hydroelectric System.—The unit cost of constructing a complete electric service system depends upon local conditions, such as nature and location of generating station, character and extent of transmission and distribution lines, contour of land and construction difficulties, cost of labor for the section, transportation facilities, and the like. In what follows a graphical analysis of construction costs is presented which shows the relative magnitudes of the different expenses as well as the unit costs represented by the construction work called for by the Tallulah Falls hydroelectric plant and transmission system of the Georgia Railway & Power Company, which serves large areas in northern and central Georgia. All of the charts are based on data presented at a meeting of the American Institute of Electrical Engineers at Philadelphia, Oct. 11, 1915 (Proceedings A. I. E. E., Vol. XXXIV, pages 2389 to 2442), by Charles G. Adsit, engineer for the Northern Contracting Company.

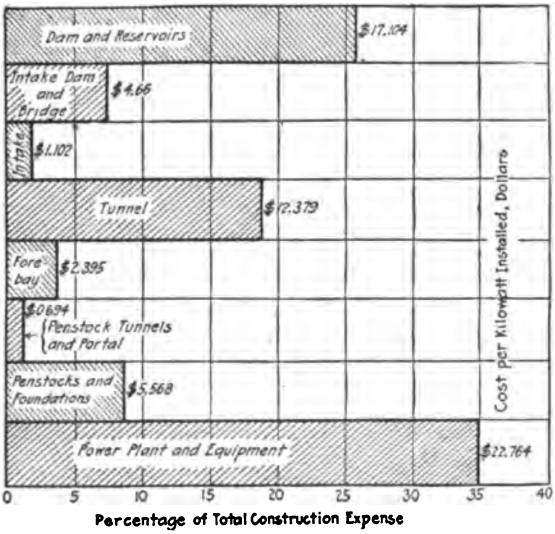

Fig. 123.—Relative Costs of Constructing Each Part of a Hydroelectric Plant

First of all, the total expenses due to constructing each part of the system, including dam, tunnel, power house and lines, are compared. Then each expense is itemized and further compared to show the relative magnitudes of labor, material, transportation and miscellaneous items. As might be expected, these data show that labor is the largest item in constructing each part of the plant. In building the dams the cost of cement, miscellaneous expenditures and cost of quarrying are next in magnitude, representing about 31 per cent. of the total expense. The expense of quarrying may be offset by the cost of sheet piling in country where the soil is such that water may seep under the dam. The plant, reinforcement and supervision costs are about equal per cubic yard of concrete laid.

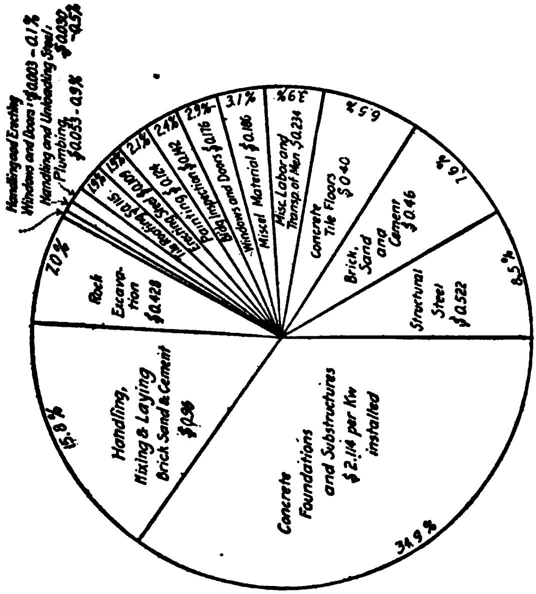

Fig. 124

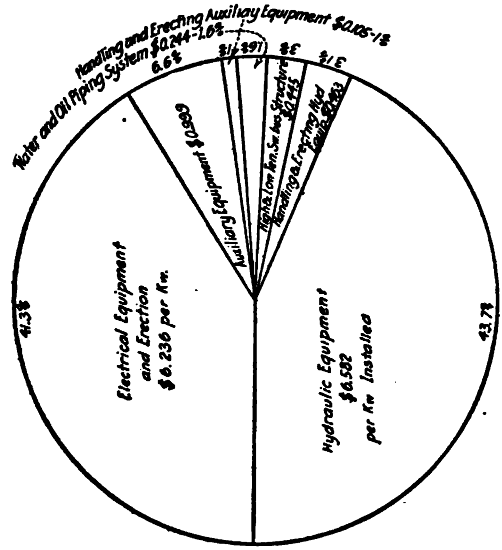

Fig. 125

Figs. 124 and 125.—Unit Construction Expenses Involved in Building and Equipping the Tallulah Falls (Ga.) Generating Station

The construction of the power house was completely described in the *Electrical World*, December 20 and 27, 1913. It consists of two main buildings, a generator house and switch house, with concrete substructure and structural-steel framework inclosed with full brick walls as a superstructure. These houses are connected by a small building, forming an H-shaped structure. The approximate volume of the generator building above the generator floor is 385,000 cu. ft., the portion below the floor about 210,000 cu. ft., and the switch house about 1,428,000 cu. ft. To the itemized building-construction expenses graphically represented above should be added $1.178 per kilowatt installed to cover a certain portion of the cost of the temporary compressor plant, spur tracks and general tool and utility equipment. The generator house contains five three-phase, sixty-cycle, 6,600 volt vertical generators, rated at 12,000 kva. maximum, directly connected to 17,000 hp. Francis-type water turbines operating under an effective head of 580 feet at 514 r. p. m.

Tunnel Costs.—Excavating the tunnel cost about one and a third times as much as lining it, these two expenses constituting about 84 per cent. of the total tunnel expense. Labor required about 65 per cent. of the total excavating expense, explosives, power and transportation making up 19 per cent. more. The cost of cement and crushing stone was a large item in lining the tunnel. It is interesting to point out here that the liability insurance for the entire tunnel construction was slightly over $2 per linear foot, of which $1.52 per foot was for excavating and 45 cents for lining the tunnel.

The cost of constructing the intake, which involved excavating about 7,000 cu. yd. of rock and placing 2,670 cu. yd. of concrete, consists of $1.517 per cu. yd. for excavating and $9.03 per cu. yd. for concreting. The construction of the surge tank, which was about 113 ft. deep and 2130 sq. ft. in cross-section, required the excavation of about 4,750 cu. yd. of rock at a cost of $2.166 per yd. About 700 tons of reinforcing steel were required in the tank and the lower 64 ft. of lining, costing $5.57 per cu. yd.

Station Buildings.—Construction of the power-house building exclusive of the tailrace cost $6.056 per kilowatt installed. Of this concreting the foundations and substructure required 34.9 per cent. Handling, mixing and laying brick, sand and cement cost 15.8 per cent. Next in magnitude were the costs of structural steel, other building material, rock excavation and tiling floors. Analyzing the equipment expense shows that the cost of furnishing and erecting the hydraulic equipment was about equal to the corresponding expense for the electrical equipment.

TABLE 28.—REPRESENTATIVE COSTS IN PER CENT. FOR HYDROELECTRIC PLANT CONSTRUCTION (AVERAGES FOR A NUMBER OF PLANTS)

KIND OF DEVELOPMENT	MAIN ITEMS OF DEVELOPMENT COST									
	(A)	(B)	(B')	(C)	(C')	(D)	(D')	(E)	(E')	(F)
Small size low-head plant	..	55	..	..	..	6	..	9	..	30
Medium size low-head plant	43	..	..	20	3	..	34	..	..	..
Small size medium-head plant	..	..	75	..	..	9	..	4	..	12
Large size medium-head plant	..	38	..	..	..	10	..	..	32	20
Large size high-head plant	22	..	..	22	17	..	39	..	..	..

where:

(A)	Total cost of dam construction.
(B'	Hydraulic work not including power house.
(B')	Hydraulic work not including power house building.
(C)	Total cost of low pressure penstock pipe.
(C')	Total cost of high-pressure penstock pipe.
(D)	Cost of Power station building.
(D')	Cost of Power station fully equipped.
(E)	Cost of turbines or waterwheels.
(E')	Total cost of hydraulic machinery.
(F)	Total cost of electrical equipment.

Table 28 considers the following items of cost for a number of plants: the Diversion Works, covering costs of dam and intake; Flume or Conduit (headrace), covering costs of flume or pipe, tunnel or canal;

Receiver, covering surge-tank, stand-pipe or secondary reservoir; Penstocks, covering cost of pipe lines (pressure lines); Power House, covering costs of hydraulic substructure and machinery, superstructure, electrical equipment, miscellaneous equipment; Tailrace, covering costs of water conduit (tailrace) construction, pipe line or tunnel and grading.

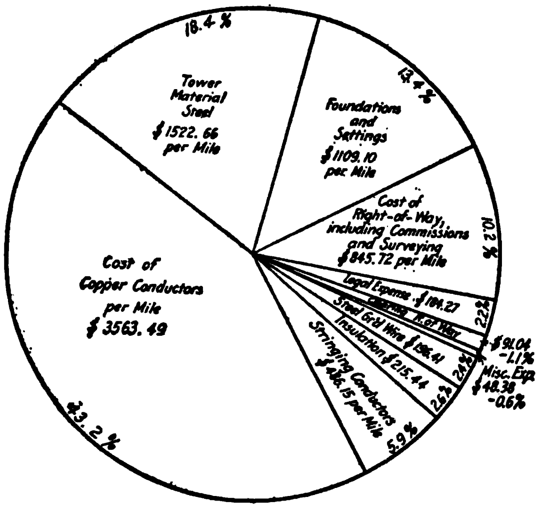

Fig. 126

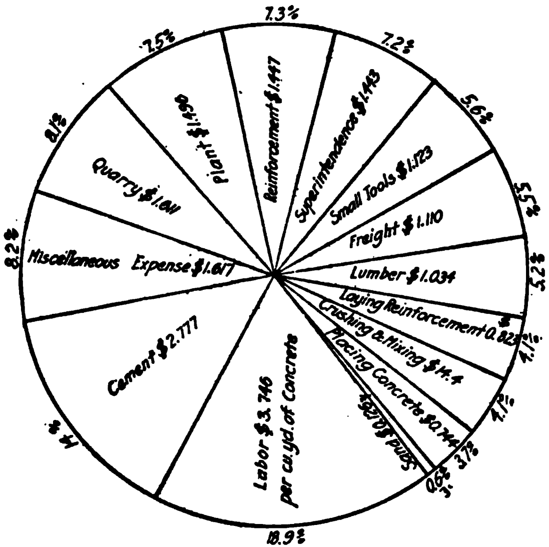

Fig. 127

Figs. 126 and 127.—Unit Costs of Constructing the Tallulah-Atlanta Transmission Line and Gravity-Type Dams.

The Tallulah-Atlanta transmission line consists of two three-phase, 110,000-volt circuits of No. 0000 eight-strand copper cables, which are arranged 9 feet apart vertically and 16 feet horizontally on four-legged double-circuit steel towers. The standard towers are spaced 650 feet to 750 feet apart. They are 66 feet high, weigh 5,544 lb., and are provided with cross-angle anchors buried 7 feet in the ground. The strain towers, which are placed about one mile apart and on each side of important crossings, weigh 6,880 lb. and are equipped with concrete footings. A 7/16 in. steel-strand ground wire is supported 3½ feet above each circuit.

Diagram Fig. 127, is based on cost of constructing two reinforced-concrete gravity-type dams, containing 38,000 cu. yd. of concrete, one 660 feet long and 93 feet high (to the crest) and the other a smaller one but provided with an underlying reinforced-concrete mattress to carry the stresses imposed on the foundations. The large expense for freightage is due chiefly to rock having to be conveyed about seven miles by rail. About 58 lb. of corrugated-bar reinforcement was used per cubic yard of concrete. The work was first undertaken under contract, but given up by contractors with considerable loss, which is included in the costs.

Transmission Lines.—In constructing the main transmission line the cost of copper was the chief expense, with the costs of tower steel, foundations and right-of-way coming next, in the order named. Branch lines from the Atlanta substation have been built to Lindale (Ga.), 69.2 miles, and Newnan (Ga.), 42.1 miles, at an expense of $4,284.05 per mile and $4,687.90 per mile respectively. Both lines are operated at 110,000 volts and consist of one No. 00 stranded-copper circuit on 70 feet double-circuit towers. The Newnan line towers also carry a 20 mile, 22,000 volt No. 0000 circuit.

Substation Costs.—The Boulevard substation at Atlanta, of the outdoor type, is designed for an ultimate capacity of 60,000 kw. All of the equipment for this rating has been installed except 30,000 kw. in transformers and control switches. The costs for this substation and other small substations are shown in Table 29.

TABLE 29.—COST OF SUBSTATIONS OF LARGE AND SMALL RATINGS

ITEM	COST PER KILOWATT	
	Boulevard Substation	Small Substation
Substructure	$0.357	$0.222
Superstructure	0.961	1.942
High-tension steel frames	0.841	1.316
Total electrical equipment	3.783	8.128
Water supply equipment	0.317	..
Total	$6.259	$11.608

The small substations are almost identical in design and similar to the substation in Atlanta. There are five of these substations in operation, with a present rating of 16,500 kw. and an ultimate rating of 30,000 kw. One substation has a present rating of 1,500 kw., three a rating of 3,000 kw., and one a rating of 6,000 kw. The ultimate rating of each of the first four is double that at present, with the 6,000 kw. station arranged for a 9,000 kw. ultimate load.

Cost of Telephone Lines.—Considerable experimenting was necessary before a satisfactory telephone-line construction was secured. The telephone line from Tallulah Falls to Atlanta was completely reinsulated, using 40,000 volt suspension-type insulators instead of the usual pin type. This work has made the unit cost appear high. The costs for about 200 miles of circuits are shown in Table 30.

TABLE 30.—COST PER MILE OF TELEPHONE LINES

ITEM	90-MILE LINE	69-MILE LINE	42-MILE LINE
Material	$299.59	$289.84	$370.63
Equipment	91.44	78.55	81.91
Construction	119.89	100.10	103.58
Total	$510.92	$468.49	$556.12

Transmission Line Costs.—Cost figures for transmission lines can be given only in an approximate way, since the size and cost of the conductor and the nature of the country passed through greatly affect line costs. However, in addition to the approximate estimates given under the heading of construction costs, page 180, attention may be called to the following items which go to make up transmission line costs. These items are cost of right-

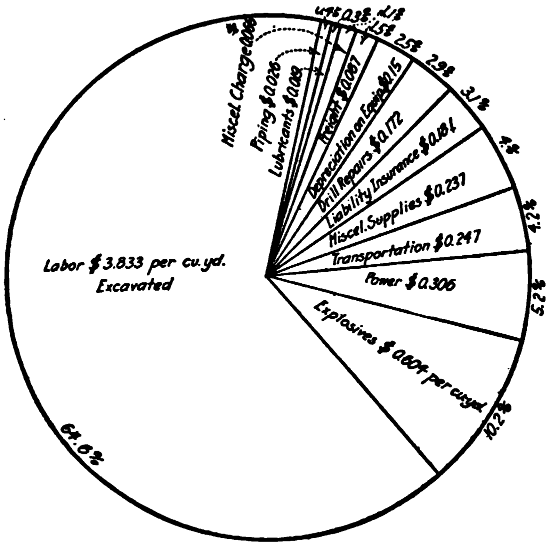

Fig. 128

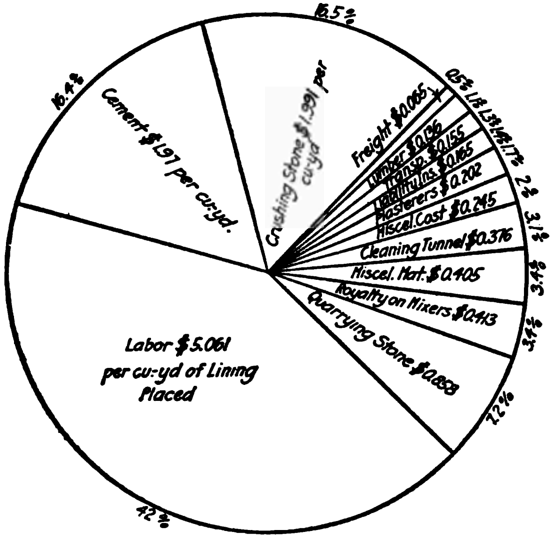

Fig. 129

Figs. 128 and 129—Analysis of Unit Costs of Excavating and Lining the Tunnel

An arch-shaped, concrete-lined tunnel 6,666 feet long, having a net cross-sectional area of 151 sq. ft. and requiring an excavation of 56,000 cu. yd., extends from the intake to a surge tank above the penstocks. Throughout the entire length hard abrasive micaceous quartzite was encountered, which caused the loss of approximately 15 lb. of drill steel per linear foot of tunnel. Water-core hammer drills were used almost exclusively. In driving the tunnel the upper-heading or bench method was abandoned in favor of the lower-heading or stopping method, the latter costing $3.779 per cubic yard in comparison with $4.315 per cubic yard by the first method. The concrete lining of the tunnel (amounting to 18,966 cu. yd.) was placed by using steel forms and injecting the mixture through 8-in. spiral pipe by compressed air. About 80 per cent. of the aggregate material used in the tunnel lining was obtained near one of the three adits to the tunnel. All sand was rolled from the rock so that only cement and supplies were transported. Grouting cost $0.0908 per square foot of lining.

of-way, cost of conductors, cost of insulators, and cost of towers. The relation of the last two items are approximately shown in Fig. 130. These curves

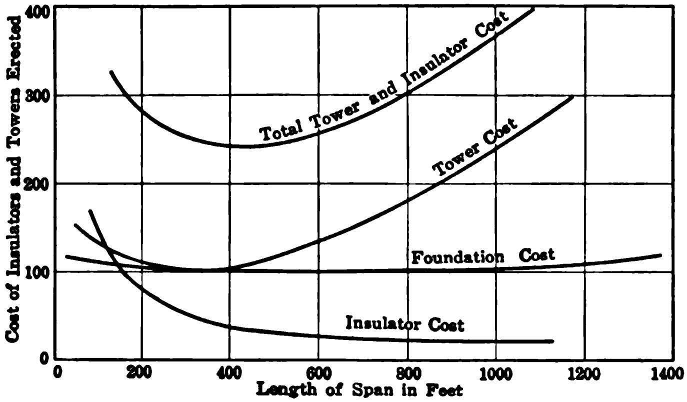

Fig. 130.—Tower and Insulator Costs in Dollars per 1000 Feet of Transmission Line

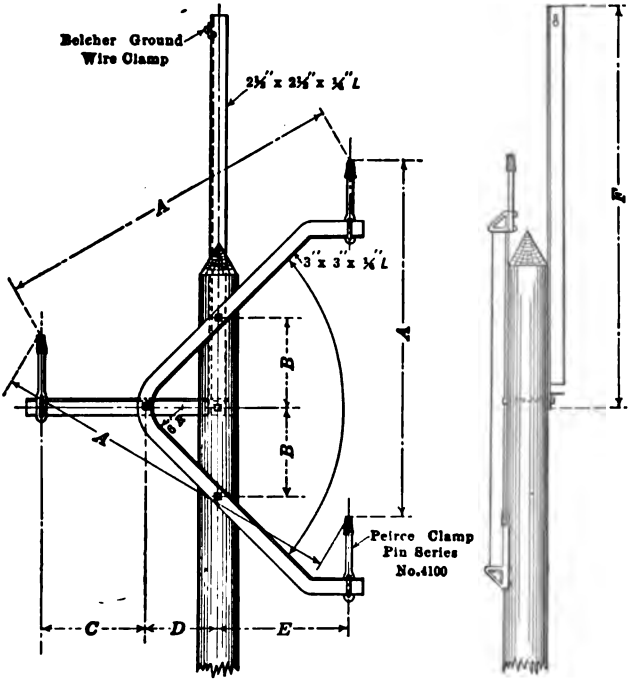

Fig. 131.—A Design of Metal Cross Arm for Voltages up to 60,000. For the 33,000 Volt Service Referred to in Table 30, A = 36 in.; B = 12.3 in.; C = 6 in.; D = 12 in.; E = 13.5 in.; and F = 50 in.

show relative costs of mechanical equipment rather than give any precise data and must not be taken except as an approximate average for lines in

TABLE 31.—TRANSMISSION LINE COSTS FOR 3-PHASE, 33,000 VOLTS USING TYPE OF POLE AND CROSS ARMS SHOWN IN FIG. 131

SIZE OF LINE		APPROXIMATE NET COST PER MILE OF MATERIAL AND LABOR						TOTAL COST PER MILE OF LINE
Conductors	Size of Poles	Poles and Cross Arms	Insulators and Pins	Ground Wire and Bayonets	Copper Wire	Telephone Line No. 10 Copper Clad	Labor and Supervision	
No. 0	35′7″	42—35′7″ @ $8.70 ea. 4—40′7″ @ 11.00 ea. 2—45′7″ @ 13.30 ea. 48—Arms @ 1.33 ea. Total Cost =$499.84	150 Insulators @ $.45 ea. 48 (set of 3) clamp pins @ $.55 ea. Total Cost =$93.90	5800 ft. 3/8″ ground and guy wires @ $11.50 per M 48 Bayonets @ .57 ea. Total Cost =$94.06	5400 lbs. @ $.16 lb. 75 lbs. No. 4 tie @ $.16 lb. Total Cost = $876.00	320 lbs. @ $.15½ lb. 48 brackets .10½ ea. 96 insulators @ $.04½ea 96 lags (½″x6″) @.03½ea Total Cost =$62.32	Labor, teaming Supervision $450.00	Poles and arms $499.84 Insulators and pins 93.90 Ground wire & bayonets 94.06 Conductors and ties 876.00 Telephone Line 62.32 Labor and Superv. 450.00 Total Cost $2076.12
No. 2	35′7″	42—35′7″ @ $8.70 ea. 4—40′7″ @ 11.00 ea. 2—45′7″ @ 13.30 ea. 48—Arms @ 1.33 ea. Total Cost =$499.84	150 Insulators @ $.45 ea. 48 (set of 3) clamp pins @ $.55 ea. Total Cost =$93.90	5800 ft. 3/8″ ground and guy wires @ $11.50 per M 48 Bayonets @ .57 ea. Total Cost =$94.06	3500 lbs. @ $.16 lb. 75 lbs. No. 4 tie @ $.16 lb. Total Cost = $572.00	320 lbs. @ $.15½ lb. 48 brackets .10½ ea. 96 insulators @ $.04½ea 96 lags(½″x6″)@.03½ea Total Cost =$62.32	Labor, teaming Supervision $425.00	Poles and arms $499.84 Insulators and pins 93.90 Ground wire & bayonets 94.06 Conductors and ties 572.00 Telephone Line 62.32 Labor and Superv. 425.00 $1747.12
No. 0	30′7″	36—30′7″ @ $5.50 ea. 6—35′7″ @ 8.70 ea. 4—40′7″ @ 11.00 ea. 2—45′7″ @ 13.30 ea. 48—Arms @ 1.33 ea. Total Cost =$384.64	150 Insulators @ $.45 ea. 48 (set of 3) clamp pins @ $.55 ea. Total Cost =$93.90	5800 ft. 3/8″ ground and guy wires @ $11.50 per M 48 Bayonets @ .57 ea. Total Cost =$94.06	5400 lbs. @ $.16 lb. 75 lbs. No. 4 tie @ $.16 lb. Total Cost = $876.00	320 lbs. @ $.15½ lb. 48 brackets .10½ ea. 96 insulators @ $.04½ea 96 lags(½″x6″)@.03½ea Total Cost =$62.32	Labor, teaming Supervision $425.00	Poles and arms $384.64 Insulators and pins 93.90 Ground wire & bayonets 94.06 Conductors and ties 876.00 Telephone Line 62.32 Labor and Superv. 425.00 $1935.92
No. 2	30′7″	36—30′7″ @ $5.50 ea. 6—35′7″ @ 8.70 ea. 4—40′7″ @ 11.00 ea. 2—45′7″ @ 13.30 ea. 48—Arms @ 1.33 ea. Total Cost =$384.64	150 Insulators @ $.45 ea. 48 (set of 3) clamp pins @ $.55 ea. Total Cost =$93.90	5800 ft. 3/8″ ground and guy wires @ $11.50 per M 48 Bayonets @ .57 ea. Total Cost =$94.06	3500 lbs. @ $.16 lb. 75 lbs. No. 4 tie @ $.16 lb. Total Cost = $572.00	320 lbs. @ $.15½ lb. 48 brackets .10½ ea. 96 insulators @ $.04½ea 96 lags(½″x6″)@.03½ea Total Cost =$62.32	Labor, teaming Supervision $400.00	Poles and arms $384.64 Insulators and pins 93.90 Ground wire & bayonets 94.06 Conductors and ties 572.00 Telephone Line 62.32 Labor and Superv. 400.00 $1606.92

general. The cost of right-of-way varies according to the value of the land in the territory crossed, and in all cases is more than the value considered for farming purposes. This cost may be taken, however, as about $200 per acre, so that a right-of-way 100 feet wide calling for twelve acres to the mile, the right-of-way cost is about $2,400 per mile. This is an additional cost not shown in the curves.

As observed from the curves, the controlling factors of line costs over and above right-of-way are tower costs and insulator costs. As the size and price of insulators is increased, the economical length of span would be increased so it follows that the higher the voltage, the longer the span. For an average voltage line, the economical span is somewhere between 300 and 700 feet, with medium weight towers (see Table 79) structure. Foundation costs are practically constant, due to the fact that the strength of the foundation against a force tending to pull it out of the ground is proportional to the weight of the foundation. Thus the cost of the foundation is proportional to this force, resulting in a practically constant value for the cost of foundation per 1000 feet of line.

Cost of Rural Lines.—As generally contended by electric service companies and forcibly brought out by the accompanying data, service can be supplied to sparsely-settled districts at a profit only by employing inexpensive line construction. There is another alternative, that of charging higher rates, but usually rates are already as high as the business will bear or as high as feasible. Therefore, any specifications which will impose stringent requirements on such lines will tend to deter developments.

The accompanying data were compiled by the 1916 committee on overhead lines of the National Electric Light Association to show that many minor distribution lines in sparsely-settled districts bring in little if any return on the investment they represent. While these data are not extensive they represent the economics of lines of this character. In addition they indicate the cost of constructing similarly equipped lines. More figures were not given for Eastern territories because few lines serving low-density loads are installed there, it being the practice of many of the larger companies not to install lines unless the revenue in sight is sufficient to make the lines profitable. The negative return on the investments represented in many cases were not shown to discourage supplying service to thinly populated territories but to point out that any legislation that requires more costly line construction may have a deterrent influence on extensions of this type. Unfortunately the data refer to lines which have been constructed during 1914 to 1916, so that the figures do not show the final financial status, since the gross revenue from a line will increase year by year if new business is developed along it. This increase, however, will be partially offset by the carrying charges on additional investment, in service connections and equipment and the increased operating and maintenance charges.

In preparing these tables interest was assumed at 7 per cent. in all cases, although it is probable that the average rate at which money was secured was over this amount. Depreciation was comprised of 8 per cent. for lines exclusive of conductors, 2 per cent. for conductors, and 3 per cent. for services, transformers and street lighting equipment. The values for operation and maintenance were taken from plant records, and where taxes were not included they were estimated at 1.5 per cent. The cost of power was included in the records submitted except in the cases of the southern California group and the first of the central California group for which an estimated cost of three-fourths of 1 cent per kilowatt-hour at the point delivered to the transmission line was assumed.

The ten groups of lines analyzed have an average length of service of 1.6 years and show an average deficit equal to 8.7 per cent. of the investment or 50 per cent. of the gross revenue. They can, therefore, be placed on a profitable basis only by increasing the rates (not feasible) on the same load or doubling the load without extending the lines. If it should take too long to double the load, however, the deficit accruing during development would be difficult to remove. It may be pointed out that several lines yielding a gross revenue of less than $200 a mile show a smaller deficit than the average because of the lower cost of construction. This is due to the use of long spans, small conductors (in some cases iron), and light construction, the initial cost, including services, being usually little if any greater than $1,000 per mile.

While the accompanying data seem to indicate that there are no returns from any minor distribution lines, indirect benefits may accrue from the general development afforded, the good-will secured from willingness to serve and the sale of otherwise surplus power.

TABLE 32.—CLASSIFICATION OF LINE INVESTMENTS* FOR MINOR DISTRIBUTION LINES

	EASTERN WASHINGTON	WESTERN WASHINGTON	CENTRAL WASHINGTON	SOUTHERN CALIFORNIA	CENTRAL CALIFORNIA		IDAHO	UTAH	ILLINOIS	CENTRAL NEW YORK	AVERAGE
Number of lines	7	6	13	4	58	..	3	5	4	2	..
Total length	100.5	3.8	40.4	150.5	109.4	100.0	29.4	52.8	31.3	12.0	630
Cost per mile:											
Right-of-way	$5	..	$32	$29	..	..	$30	$1	$80	$208	..
Physical cost exclusive of conductor	745	$585	317	534	..	..	524	500	835	1,654	..
Conductor	280	349	181	694	..	..	353	228	847	478	..
Services, transformers, street lighting, equipment, etc.	193	558	228	695	..	..	424	197	513	228	..
Overhead costs	122	298	177	33	..	..	69	74	210	182	..
Total	$1,345	$1,790	$935	$1,985	$860	$1,560	$1,400	$1,000	$2,485	$2,750	$1,610

* See table 32a for equipment of lines.

TABLE 32a.—COST AND RETURNS OF MINOR DISTRIBUTION LINES

LOCATION OF SYSTEM	CLASS OF SERVICE	NUMBER OF YEARS	LINE DATA						LOAD DATA			RETURNS AND EXPENSE IN PER CENT. OF COST						
			Length, Miles	Voltage	Poles	Span, Feet	Primary Conductors	Cost per Mile	Gross Revenue per Mile	Annual Kw.-hr. per Mile	Cents per Kw.-hr.	Gross Revenue, Per Cent.	Interest, Per Cent.	Depreciation, Per Cent.	Operation, Maintenance and Taxes, Per Cent.	Cost of Power, Per Cent.	Total Expense, Per Cent.	Net Profit, Per Cent.
Eastern Washington																		
(1)	Light and power	1	31.39	6,900	8"35′	150	3—No. 3 al	$1,105	$169	1,970	8.6	15.4	7	6.9	4.0	6.1	24.0	− 8.6
		2			7"40′	125	3—No. 8		183	2,050	8.9	16.5	7	6.9	4.6	6.6	25.1	− 8.6
(2)	Light and power	1	19.65	6,900	8"35′	200	3—No. 4 iron	1,150	184	2,510	7.3	16.0	7	7.1	4.6	6.4	25.1	− 9.1
		2			7"40′	125	3—No. 8		211	3,040	7.0	17.9	7	7.1	5.2	7.4	26.7	− 8.8
(3)	Light and power	1	25.45	6,900	8"35′	150	3—No. 3 al	1,225	171	1,235	13.8	14.0	7	6.9	3.6	5.6	23.1	− 9.1
		2			7"40′	125	3—No. 8		174	1,550	11.2	14.2	7	6.9	3.7	5.7	23.3	− 9.1
(4)	Lighting	1	1.25 (ap)	2,300	40′	120	3—No. 6	1,470	152	1.520	10.0	10.3	7	5.4	0.6	3.0	16.0	− 5.7
		3							152	1,520	10.0	10.3	7	5.4	0.6	3.0	16.0	− 5.7
(5)	Lighting	1	2.5 (ap)	2,300	40′	120	3—No. 6, 2	1.975	307	3,840	8.0	15.5	7	6.5	3.0	1.2	17.7	− 2.2
		3							375	4,680	8.0	18.9	7	6.5	3.0	1.4	17.9	+ 1.0
(6)	Light and power	1	7.5	2,300	35′	150	3—No. 0, 00	1,750	7	93	8.0	0.4	7	5.1	2.9	0.1	15.1	−14.7
		3							10	124	8.0	0.5	7	5.1	2.9	0.1	15.1	−14.6
(7)	Light, power and irrigation	1	11.75 (ap)	2,300	40′	120	3—No. 6, 2	2,045	274	3,420	8.0	13.4	7	6.2	2.6	1.0	16.8	− 3.4
		3	1.0	2,300	Undergr	ou	nd 3—No. 0		274	3,420	8.0	13.4	7	6.2	2.6	1.0	16.8	− 3.4
Total		1	100.49					$1,345	$177	1,970	9.0	13.2	7	5.8	3.6	4.2	20.6	− 7.4
		2.6							$189	2,200	8.5	14.1	7	5.8	3.8	4.5	21.1	− 7.0
Western Washington																		
(1)	Lighting	1.5	0.66	220	8"30′	146	..	$1,180	$115	1,250	9.1	9.6	7	6.0	7.0	0.8	20.8	−11.2
(2)	Lighting	1.5	1.44	13,800	*9"40′	164	2—No. 6	1,468	396	4,750	8.3	27.0	7	6.9	18.8	2.8	35.5	− 8.5
(3)	Lighting	1.5	0.5	13,800	*9"40′	142	2—No. 6	2,900	475	8,600	5.5	16.4	7	5.4	7.4	2.3	22.1	− 5.7
(4)	Large farm	1.5	0.58	13,800	9"40′	138	2—No. 6	2,290	845	18,800	4.5	37.0	7	7.4	3.4	7.0	24.8	+12.2
(5)	Lighting	1.5	0.38	13,800	*9"40′	143	2—No. 6	1,680	166	2,330	7.2	10.0	7	6.8	5.7	1.1	20.6	−10.6
(6)	Farming	1.5	0.25	2,200	9"45′	140	2—No. 6	1,990	125	1,520	7.9	6.1	7	6.6	5.0	0.6	19.2	−13.1
Total		1.5	3.81					$1,790	$385	6.350	6.1	21.5	7	6.6	9.8	3.0	26.4	− 4.9
Central Washington																		
(1)	Irrigation	1	7.2	6,600	35′	250	3—No.6&8&No.8cc	$880	$143	6,150	2.3	16.3	7	6.5	7.3	3.6	2.44	− 8.1
(2)	Irrigation	1	8.27	6,600	*35′	225	3—No. 8 cc*	850	229	9,850	2.3	26.9	7	6.9	9.4	5.6	28.9	− 2.0
(3)	Irrigation	1	0.73	6,600	35′	245	3—No. 8 cc	935	232	6,480	3.6	24.8	7	7.3	11.3	3.4	29.0	− 4.2
(4)	Irrigation	1	2.6	6,600	35′	205	3—No.8cc&No.8iron	1,065	58	2,470	2.4	5.5	7	7.0	3.2	1.1	18.3	−12.8
(5)	Irrigation	1	6.35	6.600	35′	240	3—No. 3 & 2 al	825	240	11,300	2.1	29.2	7	5.2	9.2	6.6	28.0	+ 1.2
(6)	Light and power	1	9.0	6,600	35′	225	3—Small al	976	237	5,100	4.6	24.2	7	5.7	11.5	2.5	26.7	− 2.5
(7)	Lighting	1	1.8	6,600	35′	140	2—No.8&6&No.8iron	1,290	302	3,320	9.1	23.4	7	6.1	14.4	1.2	28.7	− 5.3
(8)	Light and irrigation	1	1.18	6,600	35′	250	3—No. 8	1,015	148	1,625	9.1	14.6	7	7.1	8.0	0.8	22.9	− 8.3
(9)	Irrigation	1	0.23	6,600	35′	250	3—No. 6	2.340	500	18,450	2.7	21.4	7	7.0	8.9	3.7	26.6	− 5.2
(10)	Power	1	0.67	6,600	35′	176	3—No. 8 cc	1,090	119	321	3.9	11.3	7	7.4	7.4	0.2	22.0	−10.7
(11)	Irrigation	1	1.37	6,600	30′	170	3—No. 6	893	244	9,370	2.6	27.4	7	5.8	10.4	5.0	28.2	− 0.8
(12)	Irrigation	1	0.52	2,300	35′	195	3—No 8	1,140	488	32,800	1.5	43.5	7	6.8	9.2	14.1	37.1	+ 6.4
(13)	Irrigation	1	0.52	6,600	*35′	145	2—No. 8	870	127	458	2.8	14.6	7	7.0	8.6	0.2	22.8	− 8.2
Total		1	40.44					$935	$208	7,330	2.9	22.3	7	6.2	9.3	3.8	26.3	− 4.0

Southern California																		
(1)	Light and irrigation	1	32.68	2,400	*35′	150	4 av.—No. 6*	$2,870	$432	7,350	5.9	20.2	7	5.8	6.5	2.6	21.9	− 1.7
			35.84	15,000	40′	250	3—No. 4	1,450										
(2)	Light and irrigation	1	4.0	2,400	*35′	150	3—No. 6, 4	2,080										
			40.2	10,000	*35′	220	3—No. 6, 5, 4		170	6,340	2.7	9.1	7	5.8	5.1	2.5	20.4	−11.3
			18.2	50,000	*35′	305	3—No. 6	1,390										
(3)	Lighting	1	4.38	2,400	40′	200	3—No. 4	1,680	103	1,260	8.2	6.1	7	5.1	3.5	0.6	16.2	−10.1
(4)	Light and irrigation	1	0.26	2,400	40′	250	3—No. 6-4	1,840	460	20,600	2.2	25.0	7	6.1	6.0	8.4	27.5	− 2.5
			14.89	15,000														
Total		1	150.45					$1,985	$317	8,090	3.9	15.9	7	5.8	5.8	3.1	21.7	− 6.8
Central California		1	109.4				..	$860	$160			18.6	7	6.0	13.0		26.0	7.4
Total	†† †	2	100.0					$1,560	$310			19.9	7	6.0	23.1		36.1	16.2
Idaho																		
(1)	Light,power and irrigation	1	5.0	2,300	7″35′	200	3—No. 6	$1,580	$378	9,800	3.9	23.9	7	6.0	7.1	10.2	30.3	− 6.4
			14.5	11,000	7″35′	200	3—No. 4											
(2)	Light,power and irrigation	1	6.9	11,000	7″35′	250	3—No. 6 iron	870	174	3,480	5.0	20.0	7	7.2	5.9	8.5	28.6	− 8.6
(3)	Light and power .	1	3.0	2,300	7″35′	150	3—No. 6	1,430	698	8,000	8.7	48.8	7	6.5	6.4	110.0**	129.9	−81.1
Total		1	29.4					$1,400	$363	8,140	1.5	25.9	7	6.2	6.8	20.4	40.4	−14.5
Utah																		
(1)	Mainly light	1	2.5	2,300	7″30′	175	3—No. 6	$626	$160	1,395	11.4	25.5	7	6.1	8.7	7.9	29.7	− 4.2
(2)	Light,power and irrigation	1	8.3	2,300	7″35′	200	3—No. 6	1,060	144	3,580	4.0	13.6	7	6.1	1.5	4.7	19.3	− 5.7
			7.6	11,000	7″35′	200	3—No. 4											
(3)	Mainly light	1	6.0	2,300	7″30′	200	3—No. 6	911	184	1,025	17.9	20.2	7	6.4	2.8	5.1	21.3	− 1.1
(4)	Mainly light	1	9.5	11,000	7″35′	250	3—No. 6	1,140	128	1,230	10.4	11.2	7	6.5	3.7	3.3	20.5	− 9.3
(5)	Mainly light	1	18.9	11,000	7″35′	250	3—No. 6 iron	960	106	1,060	10.0	11.0	7	6.9	2.7	4.8	21.4	−10.4
Total		1	52.8					$1,000	$13[illegible]	1,860	7.1	13.3	7	6.5	2.7	4.6	20.8	− 7.5
Illinois																		
(1)	Light and street light	1	7.75	4,600	7″30′	100	3—No. 6	$2,170	$189	1,645	11.5	8.7	7	6.4	2.9	8.9**	25.2	−16.5
		4		2,300					220	1,870	11.7	10.1	7	6.4	3.8	6.3	23.5	−13.4
(2)	Light and street light	1	5.75	33,000	7″30′	120	3—No. 2	3,940	218	1,860	11.7	5.5	7	5.5	3.0	0.9**	16.4	−10.9
		2		2,300					271	2,320	11.7	6.0	7	5.5	3.2	1.1	16.8	−10.8
(3)	Light and street light	1	4.0	2,300	7″30′	100	3—No. 4	2,010	260	2,825	9.2	13.0	7	5.9	5.2	2.5**	20.6	− 7.6
		2							279	2,980	9.4	13.8	7	5.9	5.4	2.7	21.0	− 7.2
(4)	Light and street light	1	13.75	4,000	7″30′	125	4—No. 4	2,190	254	2,150	11.8	11.6	7	5.6	3.0	7.5**	23.1	−11.5
		3							251	2,210	11.4	11.4	7	5.6	3.3	7.2	23.1	−11.7
Total		1	31.25					$2,485	$232	2,050	11.3	9.4	7	5.5	3.2	5.3**	21.0	−11.6
		3 av							$250	2,370	11.0	10.1	7	5.5	3.6	4.8	20.9	−10.8
Central New York																		
(1)	Lighting	1	6.2	2,300	6½″*30′	101	3—No. 4*	$2,200	$263	2,250	11.7	12.0	7	6.6	3.3	3.5**	20.4	− 8.4
		2			NoteA				279	2,325	12.0	12.7	7	6.6	3.3	3.8	20.7	− 8.0
(2)	Lighting	1	5.8	2,300	6½″*35′	141	3—No. 4	3,350	314	2,340	13.5	9.4	7	6.5	2.8	2.6**	18.9	− 9.5
		2							325	2,345	13.9	9.7	7	6.5	2.8	2.6	18.9	− 9.2
Total		1	12.0					$2,750	$287	2,290	12.5	10.5	7	6.6	3.0	3.0**	19.6	− 9.1
		2							$300	2,330	12.8	10.9	7	6.6	3.0	3.1	19.7	− 8.8
Average		1.6	630 Total					$1,610	$262			17.2	7	6.1	12.8		25.9	8.7

* Principally of this size. ** Steam power. † 58 lines. †† Irrigation service chiefly—average of typical wet and dry years. ¶ See itemized costs.
Note A: About ⅜ of the poles on this line are of joint telephone ownership.

ECONOMICS OF SMALL OUTDOOR SUBSTATIONS

Service Requirements of Small Substations.—The data and brief descriptions which follow were presented by N. Nesbitt Teague in the *Electrical World*, June 10, 1916, to show examples of a successful supply of power by the use of the small outdoor substation; the cost of construction for the stations and extensions thereto; the operating and load conditions; the extent and nature of the demand and the equipment operated. These stations are operated on a 13,000 volt, three-phase, 60 cycle, isolated delta distribution network located in the South and serve industrial plants such as cotton mills, cotton oil mills, kaolin mines, silk mills, chemical and fertilizer works, etc. Twenty-four-hour service is required and interruptions to this service would cause an inestimable loss to, say, the cotton mill, where hundreds of operatives would be idle, or to the brick yard, where hundreds of bricks would be burned if the blowers were idle. Such concerns as this, whose old steam-engine advocates are yet dubious of central station service, must be pleased if the company is to hold its present customers and obtain other similar loads in its locality. Typical contracts are cited to show the nature of the agreements of the company with its consumer, and the losses and penalties for service interruptions. The following is a contract with a cotton mill served by the substation referred to in Table 42.

SECONDARY POWER CONTRACT FOR ELECTRICAL ENERGY

Agreement entered into this......day of................, 191., between the ....company, hereinafter called the "company," and the............. Manufacturing Company, hereinafter called the "customer."

Witnesseth:—For and in consideration of the mutual covenants and agreements hereinafter contained, the parties hereto agree with each other as follows:

(1) The company agrees to furnish to the customer, and the customer agrees to take from company (except when prevented by causes beyond the control of either party), for and during a period of five years beginning................, or as soon as the company shall be able to deliver energy to the customer, and a complete connection is made between the transmission lines of the company and the completely installed electrical apparatus of the customer, which shall not be later than................all electrical energy hereinafter defined as secondary power, in the form of three-phase alternating current at a pressure of approximately 13,000 volts, and at a normal frequency of 60 cycles per second with allowable variation of three per cent. (3%) above or below normal, that shall be required by the customer for the operation of its cotton mills located at................to the extent and for the operation of a maximum demand of 625 hp.

(2) By "secondary power" is meant such energy as the company agrees to furnish and supply eight months out of each consecutive twelve months' period of this agreement, and is such energy as the company reserves to itself the right to shut off and discontinue the supply thereof, by giving the customer twenty-four hours' notice of its intention to discontinue the supply, and being such energy as the customer agrees to resume the use of within twenty-four hours after the receipt by it of notice from the company that the company is ready to supply and furnish said energy to the customer, provided that the company shall not shut off and discontinue such supply during an aggregate period of more than four (4) months in each consecutive twelve (12) month period of this agreement.

(3) The customer shall pay to the company one dollar ($1) per month for each horsepower of maximum demand recorded by the instruments of the company, for all energy used between the hours of 6.30 a. m. and 6.30 p. m., and one dollar ($1) per month for each horsepower of maximum demand used between the hours of 6.30 p. m. and 6.30 a. m. The customer shall, however, have the option of paying for electrical energy used between the hours of 6.30 p. m. and 6.30 a. m., on any working day, or at any time on any Sunday at the rate of one and one-half cents (1.5 cents) per kilowatt-hour. The customer shall have the right to use electrical energy from 6.30 a. m. to 6.30 p. m. on any Sunday, for the purpose of repairs to any of its machinery, apparatus or buildings without extra charge.

The customer agrees, however, that the aggregate amount of such monthly bills shall not be less than the sum of three thousand seven hundred and fifty dollars ($3,750) per year, which shall be termed the "minimum charge."

Should the company fail to supply energy to the customer during the full period of a month as hereinafter defined in section four the charges of one dollar ($1) per month shall be reduced proportionately.

(4) A period of a day as used in this agreement shall be understood to commence at 6.30 a. m. and end at 6.30 a. m., twenty-four hours later, and a period of a month shall be considered as the days in the particular calendar month less Sundays. A horsepower shall be considered as the equivalent of 746 watts.

(5) The maximum demand shall be measured by the company on the primary side of the service transformers at a pressure of approximately 13,000 volts by such graphic recording meters as the company may install at its expense on the premises of the customer in a suitable place or building provided by the customer; and shall be considered as the maximum rate of use of the electrical energy enduring through any ten-minute period except that any maximum demand occurring on any Monday morning before 12 o'clock noon, shall not be considered. The electrical energy shall be considered as delivered at the point of measurement. Peaks due to short-circuit or accidents to the apparatus of either party to be disregarded.

(6) It is distinctly understood and agreed that in the event the maximum demand exceeds that provided in the first clause, the minimum charge as provided in the third clause shall increase in the same ratio as such increase bears to such demand.

(7) The customer agrees to pay all bills due the company within ten days after rendered, at the company's office in the city of................ If the customer shall at any time be in default of payment for more than ten days the company shall have the right to suspend the delivery of electrical energy after having given the customer ten days' notice in writing of its intention to do so. By suspending the delivery of energy for such cause the company forfeits none of its legal rights. If the customer shall at any time be in default for thirty (30) days, the company may declare this agreement void, by giving written notice of its desire to do so. Such termination shall not relieve the customer of its liability to the company, and the customer shall pay to the company as liquidating damages, but not as a penalty, the sum which should have accrued on the basis of the minimum charge in the unexpired portion of the term of this agreement.

(8) It is distinctly understood and agreed that the electrical energy to be supplied hereunder shall not be resold or used for light except in the buildings, stores, halls, churches, schools and mill tenements owned by the customer on premises where said energy is used for power purposes or the lighting of the streets of the mill village of the customer; nor by any other firm, person or corporation than the customer, nor by the customer, except upon the premises and for the purposes herein specified.

(9) The customer may increase the maximum demand by giving notice to the company six (6) months in advance of the time said increase shall go into effect. The company, however, will not reserve any power except as herein specified for the use of

the customer and will not increase the amount it shall deliver to the customer if it does not have the capacity available.

In consideration of the right to increase the maximum demand and provided the company is ready and able to supply the customer all the electrical energy it may require during the life of this agreement or any renewal period thereof the customer agrees not to use any electrical energy other than that furnished by the company except such as may be generated by the customer.

(10) Customer shall have the right to renew this agreement for a further period of five years under the same terms and conditions as this agreement in all respects, except as to the right to change from secondary to primary power as provided in section eleven hereof, by giving the company written notice of its intention to so renew, one year previous to the expiration of the first five-year period.

(11) The customer is to have the right at any time within the five years from the time this agreement goes into effect but not thereafter to change the service herein contracted for from secondary to primary power, in which case the customer agrees to pay the rate of one dollar and fifty cents ($1.50) per month per horsepower, measurement and delivery to be as provided in the fifth clause.

(12) It is understood and agreed that should the customer change this agreement or provide for the use of primary power, then and in that event the minimum charge as provided in the third and sixth clauses shall increase in the same proportion as one dollar and fifty cents bears to one dollar.

(13) All meters and other appliances and equipment, which may be at any time installed in the customer's premises at the company's expense, shall remain the property of the company. (It is understood and agreed that the company will bear the expense of necessary repairs not occasioned by the negligence or acts of the customer or its employees, to the service transformers owned by and located on the premises of the customer, provided such transformers are operated in accordance with the reasonable rules and regulations of the company.)

(14) All meters shall be tested and calibrated from time to time at the option of the company, or at the request of the consumer. Any meter tested and found not to be more than two per cent. (2%) in error shall be considered as correct and accurate. If any meter shall be found to register more than two per cent. (2%) in error, proper proportionate correction shall be made in the bill for the electrical energy extending back to the prior test, but in no event shall such correction extend back beyond thirty (30) days previous to the date on which such inaccuracy shall be discovered by such test.

(15) It is further understood and agreed that the customer hereby grants and conveys to the company the rights of ingress and egress and the right to erect poles and accessories, string its wire across or over the customer's property for the purpose of connecting to the company's service the customer's electrical installation at the point of delivery, and the removal of its poles, wires, accessories and other electrical equipment, this right to remain in full force and effect during the term of this agreement or any renewal period thereof and a reasonable time thereafter.

(16) Any question in dispute under this agreement shall be submitted to three arbitrators, one to be chosen by each party, and the third to be selected by the arbitrators thus chosen.

The decision of the majority shall be binding and conclusive upon the parties hereto.

(17) This contract is executed in duplicate and shall enure to and be binding upon the successors and assigns of the respective parties hereto.

IN WITNESS HEREOF: The parties have caused this contract to be executed by their duly authorized officers the day and year first above written.

ATTEST SIGNED:

PRIMARY POWER CONTRACT FOR ELECTRICAL ENERGY

In the event of the customer taking "primary power" the contract differs from the above somewhat as follows: (This particular contract is for service to a silk mill, data for which are given in Table 41.)

The electrical energy to be furnished under this agreement shall be "primary power," provided, however, that whenever the maximum demand as hereinafter defined shall reach 200 hp., the customer shall have the option to call for "primary power" instead of "secondary power." By "primary power" is meant such energy as the company agrees to furnish and supply every day in the year between the hours of 6 a. m. and 6 p. m. (except when prevented by the causes specified in section sixteen hereof). Nothing herein shall, however, require the customer to take electrical energy from the company exceeding a maximum demand of fifty (50) horsepower, unless or until the customer shall elect to take a maximum demand of two hundred (200) horsepower of secondary or primary power as hereinafter provided.

Until the customer shall elect to take a maximum demand of two hundred (200) horsepower of secondary or primary power, the customer agrees to pay the company for electrical energy taken each month hereunder as follows:

(a) At the rate of twenty-five dollars ($25) per year for each horsepower of maximum demand theretofore recorded by the instruments of the company between the hours of 6 a. m. and 6 p. m. of each day; and in addition thereto:

(b) At the rate of twenty-five dollars ($25) per year for each horsepower of maximum demand theretofore recorded by the instruments of the company between the hours of 6 p. m. and 6 a. m. of each day, provided, however, that the customer shall only be required to pay under this paragraph (b) the proportion of such monthly charge as the number of days in the month during which electrical energy shall be taken by the customer between the hours of 6 p. m. and 6 a. m. shall bear to the number of days in the month.

The customer agrees that the aggregate amount of payments for each year shall not be less than the sum of............dollars, hereinafter the minimum charge.

Should the company fail to supply the energy during the full period of a month, then in that event the charge per horsepower per month shall be prorated on the basis of the number of days in the month in which the energy was supplied and furnished by the company.

The following clause is part of the service contract to a cotton bagging and waste mill.

The company agrees that in case the delivery of energy to the customer shall be interrupted at any time or times between the hours of 6.30 a. m. and 6.30 p. m. for a longer period than five (5) consecutive minutes, for causes other than those specified in contract, the customer shall be entitled to payment by the company of:

0.25 cent per minute for the first hour of such interruption.

0.15 cent per minute for the second hour of such interruption.

0.083 cent per minute for the third and each succeeding hour.

A maximum demand shall be the average of daily maximum half-hour demands for the working day in each month, and shall be measured by the company on the primary side of the service transformers, etc.

Line and Substation Construction.—The species of poles used in all line construction is chestnut, classes "A" and "B," that conform to standard

N. E. L. A. specifications. Georgia pine six-pin cross-arms are used after a treatment in hot creosote. Locust pins carry O. B. and Thomas insulators. The three wires are carried on the pole and end pins. The overhead ground wire has not been used universally and extensions are usually made without this feature. Bayonets grounded on each pole are used in some instances to protect the pole from lightning. Disconnecting switches have been used freely in order that various sections may be cut off and trouble localized, without causing lengthy interruptions to other customers on the line or lines.

The method of operating this system takes into account the distribution of the load, and means are provided for more than one source of power to all customers wherever possible.

The small outdoor substations that have been installed may be constructed very economically and efficiently by using one or more poles and locating the transformers at their base. It has been found advisable to locate the transformers near the ground, instead of raising them on platforms of steel framework, since they are easily removed if necessary, much more accessible for repairs, or to obtain oil for tests, or to filter and dry out should the oil require it. A neat fence is usually built for safety protection, inclosing the installation. With this arrangement the installation will be just as safe as if the transformers were raised some 10 or 15 ft. from the ground.

When the transformers are not too heavy, and the installation does not warrant the cost of a concrete foundation, a couple of old iron rails imbedded in the earth serve the purpose very well. Where the transformers are large and heavy, steel tower structures with concrete bases, or steel frame bases, are installed, but the units are not raised more than 1 foot off the ground.

Switches, Fuses, Arresters and Meters.—The switches and fuses used on these stations are Burke horn gap, General Electric types D-7 and LG-9 and Delta Star designs. Due to the high cost of replacing the chemically filled fuses, home-made horn type fuses have been placed on this equipment, and in some instances these fuses have been placed directly on top of the transformers so that they are accessible to renewal. The switches are arranged to operate from this location. Aluminum, copper, etc., string fuses are tested before they are installed.

Lightning is the cause of the most serious operating troubles in this locality, therefore the selection of the proper arrester is vital. Lines and stations have been equipped with designs other than the electrolytic aluminum cell type, but, of course, it is doubtful if the desired result of protecting electrical equipment from surges or the lightning menace has been accomplished. It is hoped that the installation of reactors, in some cases, between outside lines and the equipment, to drain off the surge through horn gaps to ground, has minimized the damage to transformers and inside apparatus;

however, they do not offer full protection to line insulators nor take care of high frequency. The aluminum cell type of arrester has met the demand most desirably and has been installed whenever the installation warrants its cost and especially at the end of the lines.

The meters are usually located directly on the installation or in an adjacent building. The metering has been performed on the primary side, or the secondary side of the installation, according to conditions or the desires of the customer. In general when metering on the 13,000-volt side, the potential and current transformers are housed in special boxes and the meter placed in the same box on the pole adjacent to transformers or near them. The meter is mounted so as to be accessible for test and easily read through a glass in the front door. It is installed on a pole when the metering is done from the secondary side. Polyphase watt-hour meters are used to record the kilowatt-hour consumption, and where required, maximum demand or graphic recording wattmeters are used.

In general the only disadvantages which are pointed out by the advocates of in-door substations are: the greater risks to the public, the difficulty in making repairs and the less reliability to service. In the installations made, the first objection is remedied by the wire fence, and the latter is not so objectionable in the South, where there are few snow or sleet storms.

TABLE 33—COST OF SUBSTATION CONSTRUCTION TO SERVE A COTTON SEED OIL MILL

The substation is rated as 900 kva. The primary voltage is 13,000, 3 phase, 60 cycle, and the secondary 440 volts. This installation is located 25 feet from the main distribution line.

COST ITEMS

Foundations	$ 105.00
Three 300 kva. transformers (G. E.)	2,416.00
One set G. E. type LG-9, 300 amp. 22,000-volt switches	110.38
One set G. E. electrolytic aluminum cell arresters	321.75
Steel framework, complete	91.00
Hardware, material, etc.	105.32
Labor	180.77
Meter and current transformers	95.00
Total cost of substation	$3,425.27
Cost per kilovolt-ampere	3.80

CONTRACT DATA

Duration of contract	Five years
Horsepower contracted for	1,200 to 1,500
Hours of service	Twenty-four
Months of service	Eight
Service charge per kilowatt-hour used	6.6 mills
Guaranteed minimum per year	$6,000
Kilowatt-hours consumed per month	289,900
Gross revenue per month	$1,913

The installation serves a cotton seed oil mill and cotton seed feed mills. The following is the motor equipment: Three 150 hp. General Electric slip ring form M; three 150 hp. Westinghouse form HF.; and two 50 hp. General Electric squirrel cage form K motors.

It is understood that the customer has the privilege of canceling the contract at the end of two years by giving ninety days' notice and the payment of $1,000 as liquidating damages, but not as a penalty. Under the same conditions the contract may be terminated at the end of three years by the payment of $800, and at the end of four years by the payment of $300.

TABLE 34—COST OF SUBSTATION CONSTRUCTION TO SERVE A CHEMICAL FERTILIZER WORKS

The installation is rated at 200 kva. The primary voltage is 13,000, three-phase, 60 cycles; secondary 220 volts, two-phase. The substation is located 4800 ft. from the main distribution line.

SUBSTATION COSTS

Two 100 kva. General Electric transformers, one Westinghouse meter, Delta Star switches and fuses	$1,500.00
Poles, cross-arms, insulators and hardware	37.56
One set General Electric electrolytic aluminum cell arresters	365.50
Copper for bus	12.50
Fence and miscellaneous	50.00
Labor	90.00
Total cost of substation	$2,054.56
Total cost of extension	$960.01
Total cost of extension plus substation	$3,014.57
Cost per kilovolt-ampere (extension plus substation)	15.00
Cost per kilovolt-ampere (substation only)	10.00

CONTRACT DATA

Duration of contract	Five years
Horsepower contracted for	250 aggregate normal rated capacity in motors
Hours of service	Twenty-four for eight months
Service charge per kilowatt-hour used	11.0 mills
Guaranteed minimum payment	$1,500.00
Actual kilowatt-hours consumed per annum	173,300

Power is used for the manufacture of fertilizer. The following motors are operated: One 150 hp. General Electric form P slip-ring; one 35, two 25, and three 5 hp. General Electric form K squirrel cage. Transformers are Scott connected.

TABLE 35—COST OF SUBSTATION CONSTRUCTION TO SERVE A COTTON BAGGING AND WASTE MILL

The installation required is rated as 750 kva. The primary voltage is 13,000, three-phase, 60 cycle; secondary 550 volts, three-phase.

COST OF EXTENSION

One Westinghouse polyphase meter; one curve drawing wattmeter and equipment	$ 450.00
Nine disconnecting switches	99.00
No. 4 H. D. copper guys and strains	98.25
R. C. wire	100.00
Poles, cross-arms, insulators and hardware	98.00
Conduit	93.50
Labor	160.00
Total cost of extension	$1,098.75

CONTRACT DATA

Duration of contract	Five years
Horsepower contracted for	970 maximum
Hours of service	Twenty-four for twelve months
Service charge per horsepower per month	$1.25
Guaranteed minimum payment	$2,750 yearly

The customer furnished the substation, transformers and all such equipment. The contract is for secondary power to be used as follows: In the bagging mill by one 200 hp. General Electric synchronous motor; four 35 hp. and two 50 hp. General Electric squirrel cage motors; in the waste mill by one 100, one 75, two 50, two 35, and two 5 hp. General Electric squirrel cage induction motors, and five 20, one 15, and two 35 hp. General Electric squirrel cage induction motors used on hoists and miscellaneous apparatus. The meter is placed in superintendent's office, some 400 feet from installation.

TABLE 36—COST OF SUBSTATION CONSTRUCTION TO SERVE A FERTILIZER PLANT AND OIL MILL

The installation required is rated at 600 kva. The primary voltage is 13,000, three-phase, 60-cycle; secondary 220 volts, two-phase. The substation is located 400 feet from the main distribution line.

SUBSTATION COSTS

Two 300 kva. Westinghouse transformers	$1,700.50
Three General Electric type D7 fuses and switches	56.70
Poles, insulators, cross-arms and hardware	43.00
Copper for bus	88.78
Meter and equipment	312.60
Meter house	37.40
Fence	25.00
Labor	67.00
Total cost of substation	$2,330.98
Cost of extension	258.00
Cost per kilovolt-ampere, extension plus substation	4.31
Cost per kilovolt-ampere, substation only	3.88

CONTRACT DATA

Duration of contract	Five years
Horsepower contracted for, 200 on basis of 475. This basis to increase in same proportion as motor installation increases.	
Hours of service	Twenty-four for eight months' minimum
Service charge per horsepower per month	$0.75
Additional charge per kilowatt-hour used	5.0 mills
Guaranteed minimum payment	$1,800
Gross revenue from September to February	$4,364

The transformers are Scott connected and furnish power for the following motors: One 100, one 150, one 60 hp. General Electric slip-ring form M motors used in the press and linter rooms. Two 50 hp. General Electric squirrel cage form K motors in the cake mill. The following General Electric squirrel cage form K motors: one 35 on an elevator, one 5 in shop, one 10 and one 15 in fertilizer plant and two 150 hp. slip-ring to be installed on liters. The above rates apply during the customer's operating season. Electric energy used after the close of the regular operating season or during the period known as the dormant period, shall be paid for at the company's regular retail rates. During the operating season current used for lighting shall be billed under this contract; during dormant period to be paid at the company's regular lighting rates.

TABLE 37—COST OF SUBSTATION CONSTRUCTION TO SERVE A COTTON OIL MILL

The installation is rated at 300 kva. The primary voltage is 13,000, 60 cycle, three-phase; secondary, 220 volts, three-phase. The installation is located 2450 feet from the main distribution line.

COST ITEMS

Three 100 kva. Westinghouse transformers	$1,350.00
Three 15,000 volt, 30 amp. General Electric type D7 switches and fuses	56.10
Poles, insulators, cross-arms and hardware	35.90
Copper for bus	14.48
Watt-hour meter and equipment	120.00
Labor	45.00
Fence, paint and miscellaneous	40.40
Total cost of substation	$1,662.48
Total cost of extension	875.52
Total cost of extension plus substation	$2,538.00
Cost per kilovolt-ampere (extension plus substation)	8.46
Cost per kilovolt-ampere (substation only)	5.54

CONTRACT DATA

Duration of contract	Two years
Horsepower contracted for	350
Hours of service	Twenty-four for eight months
Service charge per kilowatt-hour	8.8 mills
Guaranteed minimum payment	$1,350.00
Gross revenue per eight months	4,992.00

The above rates apply during customer's operating season, the customer being allowed to disconnect service, and no charge being made during the shutdown or dormant period. The power is used for cotton-seed houses and oil mill. The plant operates the following motors: One 100 and one 150 hp. slip-ring General Electric form M; one 10, one 75 and three 50 hp. squirrel cage General Electric form K, and two 50 hp. slip-ring form M Wagner motors.

TABLE 38—COST OF SUBSTATION CONSTRUCTION TO SERVE AUTO TIRE PLANT

The installation required is rated at 300 kva. The primary voltage is 13,000, three-phase, 60 cycles; secondary, 220 volts, two-phase. The substation is located 4000 feet from the main distribution line.

SUBSTATION COSTS

Two 150 kva. General Electric transformers and Westinghouse meter	$1,350.00
One set Delta Star fuse switches and arresters	160.00
Disconnects rack and copper for bus	86.00
Meter box	35.00
Poles, cross-arms, insulators and hardware	21.00
Fence and miscellaneous	30.00
Labor	648.00
Total cost of substation	$1,730.00
Total cost of extension	1,366.00
Total cost of extension plus substation	$3,096.00
Cost per kilovolt-ampere (extension plus substation)	10.30
Cost per kilovolt-ampere (substation only)	5.76

CONTRACT DATA

Duration of contract	Five years
Horsepower contracted for	200
Hours of service	Twenty-four for twelve months in 1915
Service charge for horsepower per annum	$9.00
Additional charge per kilowatt-hour used	1.0 cent
Guaranteed minimum payment	$150 per month
Actual kilowatt-hour consumed per annum	138,596
Gross revenue per annum	$2,132.00

The transformers are Scott connected, furnishing power for the following motors: One 150, one 75, one 35 and five 5 hp. Westinghouse slip-ring and two 7½ hp. General Electric squirrel-cage motors.

TABLE 39—COST OF SUBSTATION CONSTRUCTION FOR COTTON OIL MILL AND GIN

The installation called for a total rating of 450 kva. The primary voltage is 13,000, three-phase, 60 cycles; secondary, 550 volts, three-phase. This substation is located 6500 ft. from the main distribution line.

SUBSTATION COSTS

Three 150-kva. General Electric transformers	$2,650.50
One set of Delta Star arresters and fuses	150.00
Copper for bus	30.59
Three disconnects	31.50
Two meters	80.00
Poles, cross-arms, insulators and hardware	50.01
Labor	170.00
Fence, paint and miscellaneous	40.40
Total cost of substation	$3,203.00
Cost of extension	2,049.00
Cost of extension plus substation	$5,251.00
Cost per kilovolt-ampere (extension plus substation)	11.70
Cost per kilovolt-ampere (substation only)	7.10

CONTRACT DATA

Duration of contract	Five years
Horsepower contracted for	480
Hours of service	Twenty-four
Service charge per horsepower per month	$0.75
Additional charge per kilowatt-hour used	5.0 mills
Guaranteed minimum payment	$1,800.00 per year
Actual kilowatt-hours consumed per year	1,091,094
Gross revenue per year	$6,659.00

The metering is done on the secondary side of the transformers. The power is used by the following General Electric motors: Two 50, one 75 form K squirrel-cage induction motors; one 75, one 100 form M slip-ring motors; one 200-hp. form L internal resistance induction motor.

TABLE 40—COST OF SUBSTATION CONSTRUCTION TO SERVE A KAOLIN MINE

The installation required is rated at 150 kva. The primary voltage is 13,000, three-phase, 60 cycles; secondary, 550 volts, three-phase. The substation is located 7900 ft. from the main distribution line.

SUBSTATION COSTS

Three 50-kva. General Electric transformers	$963.00
Burke horn-type switches, fuses, disconnects	300.00
Meter and equipment (Westinghouse)	220.00
Poles, insulators, cross-arms and hardware	51.69
Copper, guys, etc.	21.91
Labor	38.00
Fence, transportation, miscellaneous	49.00
Meter house	37.40
Total station costs	$1,681.00
Cost of extension	1,372.00
Total cost extension and station	$3,053.00
Cost per kilovolt-ampere (extension and station)	20.35
Cost per kilovolt-ampere (station only)	11.20

CONTRACT DATA

Duration of contract	Two years
Horsepower contracted for	100
Hours of service	Twenty-four for twelve months
Service charge per horsepower per month	$0.75
Additional charge per kilowatt-hour	11.0 mills
Guaranteed minimum payment	$100.00 per month

Metering is done on the primary side of the transformers. The customer furnished right-of-way for power lines. Power used by Wagner slip-ring motors for hoists, shovels to remove the over-burden, grinding and conveying the product, in the mining of kaolin (chalk), which is sold for paper making.

At the expiration of the contract the customer has the privilege of renewing from year to year at the above specified rates.

Poles for power line are spaced from 200 to 300 ft. apart.

Table 41—Cost of Substation Construction to Serve a Silk Mill

This installation is rated at 225 kva. The primary voltage is 13,000 three-phase, 60 cycles; secondary, 550 volts, three-phase. The substation is located 250 ft. from the main distribution line.

Cost of Installation

Poles, cross-arms, insulators and hardware	$105.60
Westinghouse graphic and watt-hour meters, current and potential transformers	450.00
Meter, box, transformer, framework, etc.	65.00
One set Delta star switches, fuses and arresters	150.00
Disconnects	65.00
Wire and conduit	76.60
Labor, paint and miscellaneous	150.50
Total cost	$1,062.70
Cost per kilovolt-ampere	$4.70

Contract Data

Duration of contract	Five years
Horsepower contracted for	214 in the day and 27 at night
Service charge per horsepower per year	$25.00 of maximum demand
Guaranteed minimum payment	$1,200.00 per year
Gross revenue for twelve months, 1915	$2,452.00

The customer furnished transformers and contracted for primary power. In event secondary power is used the rate is to be reduced to $1.25 per month per horsepower and minimum charge to be $2,400.00. If primary power for a maximum demand of 200 horsepower is used the rates will be $20 per year per horsepower of maximum demand and the minimum charge shall be $4,000 per year. General Electric form K squirrel cage motors are used.

Table 42—Cost of Extension Construction to Serve a Cotton Mill

This installation is rated at 750 kva. The primary voltage is 13,000, three phase, 60 cycles; secondary 550 volts, three phase. The substation was furnished by the consumer and is located 500 ft. from the main distribution line.

Cost of Extension

40-ft. poles	$16.00
Cross-arms, insulators and hardware	45.20
Disconnects	72.00
No. 2 H. D. copper	50.00
Labor	52.00
One Westinghouse graphic meter	111.05
One Westinghouse watt-hour meter	37.94
Two potential transformers	229.31
Two current transformers	71.64
Total cost	$685.14

Contract Data

Duration of contract	Five years
Horsepower contracted for	737 in the day and 134 at night
Hours of service	Twenty-four
Service charge per horsepower per month	$1 per horsepower of maximum demand or optional $0.015 per kilowatt-hour
Actual kilowatt-hours consumed in 1915	1,896,660
Gross revenue on demand basis	$9,985.00
Guaranteed minimum payment	$5,100 per year

Secondary power is contracted for, and if at any time a change is made calling for primary power the cost will be $1.50 per horsepower per month. The equipment of this mill consists of the following motors, which drive some 27,000 spindles: three 75-hp., twelve 50-hp., and one 5-hp. form L, General Electric mill motors.

Cost of Iron Pipe, Outdoor Substations.—The cost of constructing small outdoor substations such as shown in Figs. 132 and 133, are given in Table 43. These substations are operated on the system of the Ohio Service Company and serve industrial loads in Strasburg and Dennison, Ohio. The supports are made of standard pipe assembled at small cost by the line crew.

TABLE 43.—COST OF TYPICAL SUBSTATIONS OF OHIO SYSTEM

COST OF 150-KW., 13,200-VOLT SUBSTATION (See Construction Drawings)		
80 ft. 6 in. pipe (second hand) at 60 cents per foot		$48.00
Channels, angles, bolts, etc.		40.00
Wood plankings and busbar supports		15.00
Foundation, concrete, etc.		20.00
Labor, erecting, etc.		35.00
Structure expense		$185.00
Three 50-kw. transformers		1,125.00
One electrolytic arrester		325.00
One Delta Star C. R. E. three-phase unit		210.00
Labor, freight and electrical connections		30.00
Electrical expense		$1,690.00
Total substation cost		1,848.00
Cost per kilowatt installed		2.32
COST OF 300-KW., 33,000-VOLT SUBSTATION (See Construction Drawings)		
Structure—8 in. pipe and fixtures		$185.00
Three 100-kw., 33,000-volt transformers	$2,000.00	
Electrolytic arrester	600.00	
One Delta Star three-phase C. R. E. unit	310.00	
Labor, freight and electrical connections	45.00	
Electrical expense		$2,955.00
Total substation cost		3,140.00
Cost per kw.		10.45

Unit Costs of Small Outdoor Substation Equipment.—As outdoor substations increase in size the cost per kilowatt rapidly decreases. The costs of two installations serve as an example: A 25-kw., single-phase, 22,000-volt, 25-cycle substation with wooden poles and platform construction installed, cost approximately $22 per kilowatt, or $550. This cost includes the following items: Transformer, $13 per kilowatt; switching and protective equipment, $5 per kilowatt; structure material and labor, $4 per kilowatt. A 900-kw., three-phase, 22,000-volt, 25-cycle steel-tower substation installation cost $4,398.18, this being $4.88 per kilowatt, divided as follows: Material cost, including transformers, $4.33 per kilowatt; labor cost, 55 cents per kilowatt. The labor cost on this particular station included hauling the transformers a considerable distance over poor roads, which constituted practically half the total labor cost.

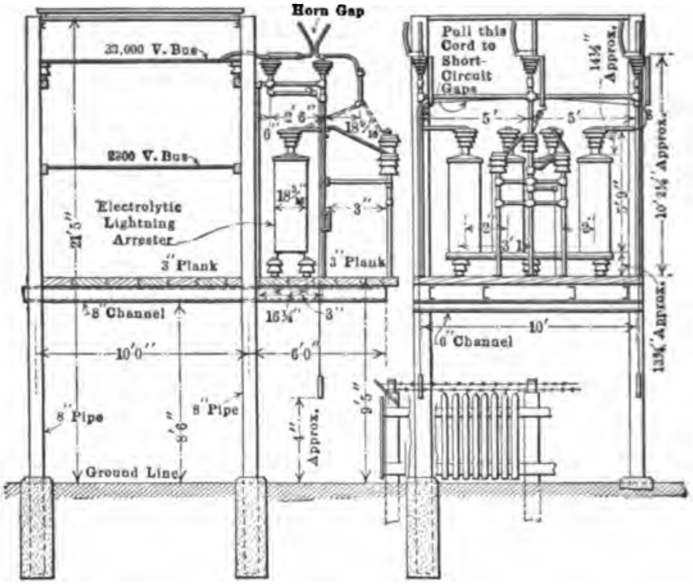

Fig. 132.—Construction of a 33,000 Volt Outdoor Substation to Serve Industrial Loads

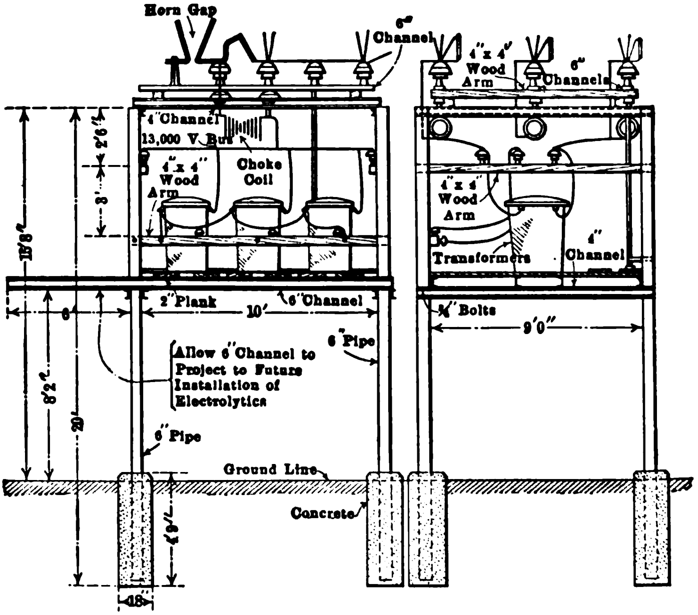

Fig. 133.—Construction of a 13,000 Volt Outdoor Substation to Serve Industrial Loads

For stations from 50 kw. to 3200 kw. at 13,200, 22,000 and 33,000 volts, three-phase, the costs per kilowatt of the complete high-tension switching, fusing, choke coil and lightning arrester equipment are given in Table 44.

TABLE 44.—NET COSTS PER KW. OF EQUIPMENT WITH 100 PER CENT. OVER-FUSING ON HIGH-TENSION SIDE (DELTA-STAR ELECTRIC COMPANY, CHICAGO, ILL.)

Voltage Three-Phase	Size in Kw.	Cost Per Kw. in Dollars				
		A	B	C	D	E
13,200	50	$5.00	$6.00	$6.90	$0.022	$3.50
	100	2.32	3.07	3.52	0.0138	1.75
	250	1.00	1.26	1.45	0.008	0.89
	500	0.50	0.66	0.75	0.0053	0.35
	1000	0.28	0.35	0.40	0.0037	0.18
	2000	0.15	0.19	0.21	0.0022	0.12
22,000	50	5.50	7.30	8.20	0.022	3.50
	100	2.75	3.65	4.10	0.011	1.75
	200	1.40	1.86	2.05	0.0069	0.88
	400	0.72	0.95	1.06	0.005	0.44
	800	0.40	0.52	0.57	0.0133	0.22
	1600	0.23	0.27	0.30	0.0024	0.11
	3200	0.14	0.15	0.16	0.0014	0.09
33,000	50	6.00	8.00	9.80	0.022	3.50
	100	3.25	4.25	4.90	0.011	1.75
	200	1.70	2.16	2.50	0.0143	0.88
	500	0.74	0.94	1.07	0.0135	0.35
	1000	0.40	0.50	0.57	0.0039	0.22
	2000	0.21	0.27	0.30	0.003	0.11

Column A covers the cost of double break per phase, three-pole switches and simple horn-gap arresters. Column B gives data for an installation which is the same as A, except that the arresters have limiting resistors in the grounded circuit. Column C presents data for equipment which is the same as A, except that arresters are of the high-speed sphere-gap resistor type. Column D gives the cost per kilowatt per phase of chemical fuse renewals. The cost per kilowatt of hot galvanized steel tower frames is given in column E. Especial attention is called to the rapid decrease in cost with increase of transformer rating.

CHAPTER VI

SYSTEM OPERATION AND ECONOMICS

Relay Protection.—The control and operation of electrical distribution and transmission systems, which are continually becoming more complicated, present engineering problems in the proper design and installation of protective apparatus which demand the most careful attention. Much depends on the continuity of service, and protective apparatus is now designed with this in view. Experience has shown that no single part of an electrical system is free from the possibility of injury, either accidental or unavoidable as may be the case. The expensive machinery and apparatus used in modern central stations and long distance high-voltage transmission make it absolutely necessary to provide reliable automatic means for disconnecting generating units, transformers, transmission lines and distributing feeders at certain critical moments, both for the protection of the apparatus itself and for the maintenance of an uninterrupted and successful operation of the system.

A large number of different types of relays are in use, but only the essential designs in ordinary use need be discussed. The protective relay may be of the open or closed-circuit type. Either may be instantaneous or have a time-limit in its action, and types are available for single-phase, two-phase or three-phase circuits. Two series transformers and two single-phase relays or a double-pole relay are required for a two-phase circuit. For a three-phase circuit three series transformers may be required to protect the circuit though usually only two series transformers and two single-phase relays or one double-pole relay will provide adequate protection. The following considerations are important for the protection of station apparatus and lines.

Generators.—Usually, generators are not arranged for automatic disconnection from the system which they supply, upon the occasion of a fault developing within their windings or their connections to the main buses, as in the cables, etc. With the great amount of power being concentrated in some systems of today, it becomes advisable, therefore, to sectionalize the buses with current-limiting reactances, or even introduce external current-limiting reactances in each separate generator, in order to limit the amount of short-circuit current which may flow into a fault. If relays are used, their action will be somewhat slower inasmuch, as the current flow will be considerably less, thereby giving selective action. Reverse current relays are used in many cases to operate signals to indicate reversal of current in generator circuits, but under all conditions the judgment and movements of the operator are usually depended upon for proper operation of the generator switches.

It is of utmost importance to keep the generators in service. In general, therefore, as the possibility of trouble between the generators and the buses is rather remote, the switches may be non-automatic or equipped with definite time limit relays and arranged to trip the generator switch as a last resort, after the automatic switches more remote from the generators have failed to isolate the trouble. For a very simple transmission system consisting merely of one generator and step-up transformer, a single transmission line and step-down transformer, it is self-evident that the only protection required is an automatic generator switch which should preferably be provided with the time limit relay (either of definite or inverse action) so as to prevent the tripping of the switch on momentary short-circuits, such as the swinging together of the line conductors.

Power Transformers.—Power transformers developing internal short-circuits in a group of two or more operated in parallel, may be selectively disconnected from the circuit by an instantaneous relay sufficiently sensitive to operate on a small current reversal, in order to minimize damage. Oil switches should always be installed on both sides of transformers. In case of trouble in one group selective action should be provided so that the injured group can be disconnected immediately without interrupting the other groups. Ordinarily this is accomplished by means of instantaneous differential relays, consisting of two coils connected to current transformers in either side of the transformer groups. The effect of one coil neutralizes that of the other, but on a reversal of current through one of the coils, each coil assists the other in operating the relay, thus instantaneously opening both the high-voltage and low-voltage transformer switches. For protection against overloads, inverse-time-limit relays are usually installed for the low voltage transformer switches and instantaneous differential balance relays for the high-voltage switches. When a short-circuit occurs in one of the groups, the relay for its high-voltage switch will then act on the reversal of the current and instantly open the switch, at the same time locking the relay of the other high-voltage transformer switches, and thus prevent them from opening on overload. The low-voltage switch of the faulty group of transformers therefore opens, thus selectively disconnecting the injured group before an interruption of the electrical service takes place.

Relay Protection for Transmission Lines.—Invariably transmission systems are eventually extended to include territory not planned in the original scheme for development, thus giving rise to peculiar operating conditions requiring special relay applications to obtain satisfactory selective action. At the present time a large single high-voltage long-distance transmission line is seldom found. The general practice is to operate two or more transmission lines in parallel, either of which will carry the entire load under emergency conditions, thus calling for a relay to cut out automatically the faulty line or section of line without interrupting service. Relay protection for transmission lines varies with methods of operating different systems, but in general either instantaneous inverse-time-limit or definite-time-limit types of relays are used.

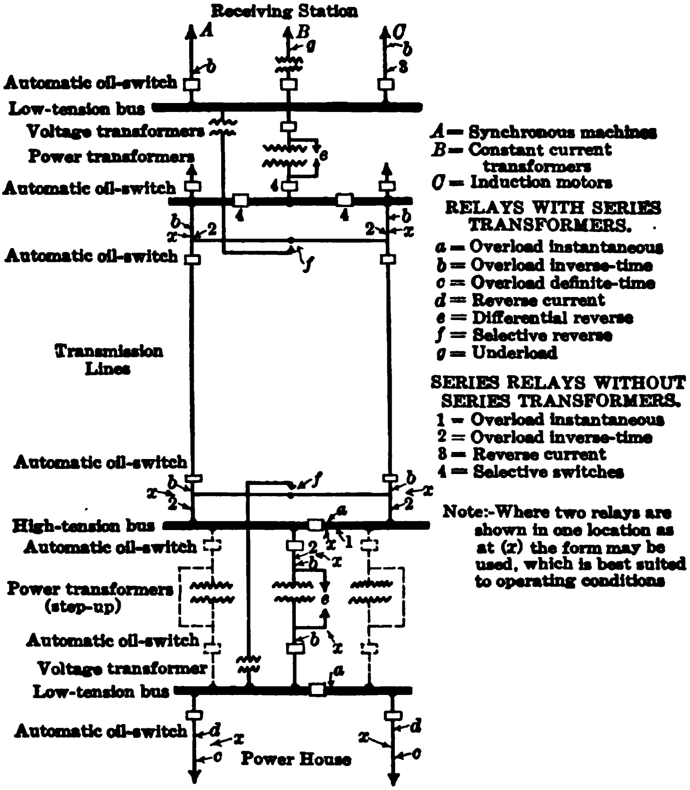

Fig. 134.—Full Automatic Protection by Means of Relays (Primary and Secondary) Showing the Proper Form of Relay for any Given Location

For systems operating radial feeders, with each feeder connecting to only one substation and not operating in parallel at the substation ends, reasonably satisfactory service has been rendered by the types of relays referred to above. In systems operating ring-systems of feeders, or radial feeders with several substations in tandem on a single feeder, where selective adjustments are required between different relays in order to prevent interruptions of service from all stations between a fault and the source of power, satisfactory results have not always been attained with any of the above-mentioned types of relays.

Service Protection by Relays.—As an example of the service possible from a correctly designed system of sectionalizing relays may be cited the case of a long-distance transmission company supplying power to an important industry which a few years ago suffered more than 25 interruptions annually. A systematic study of the sectionalizing problem was made, which resulted in a comparatively small expenditure for relays and a slight rearrangement of switching apparatus. As a reward for this work the service to the important customers on the system is now almost perfect, and the company officials expect in the future not more than one interruption annually from all causes. This system contains more than 1400 miles of transmission line and suffers not less than 100 short-circuits and grounds per year; nevertheless, the chance for an extensive interruption from line trouble is now much less than from an accident in a generating station.

Such service frequently pays for itself in a conspicuous way, as in the case of a hydroelectric system which for years had maintained an auxiliary steam plant on a hot stand-by basis. As the result of the installation of a complete automatic sectionalizing scheme it was found possible to place this plant on a cold stand-by basis, thus effecting a large saving.

Another direct financial benefit from a relay installation is the saving in copper which results from the use of a closely inter-connected system. Sometimes a power customer demands a separate set of feeders from the generating station, in order that his service may not be disturbed by troubles on the remainder of the system. Such practice requires an uneconomical amount of copper because the diversity factor of the system cannot be utilized. A proper equipment of relays will allow the use of tie lines and of other inter-connections, with the result that more load can be carried and the service to each customer will be improved because more sources of power will be available.

The object of protective relays is to secure continuity of service, and this applies whether the relays are installed so as to disconnect defective sections of line or to disconnect apparatus which is in danger of causing trouble or which has already become a source of disturbance. Although the apparatus and methods used are continually permitting more reliable service, at the same time electrical systems are increasing in size, with a resulting increase in causes and chances for disturbance. It is, therefore, necessary to install sectionalizing devices before perfect service can be secured.

Interruptions.—Any disturbance which will cause a loaded induction motor to stop may be called an interruption. The disturbance that can be withstood depends upon the nature of the load and the characteristics of the motor, but it may be safely stated that any motor can have the voltage at its terminals reduced to zero for at least two seconds without affecting it. The only method of handling disturbances which will be considered will be the method of automatically disconnecting any section of line or piece of apparatus which is creating trouble. Other methods of clearing disturbances without disconnecting the lines may be used, such as the use of arc suppressors and voltage-killing devices. It should be further realized that existing types of relays cannot clear grounds unless they amount to short-circuits, as in the case of a grounded neutral system. A ground on an isolated neutral system will not ordinarily cause an interruption unless it should develop into a short-circuit, in which case sectionalizing relays will operate.

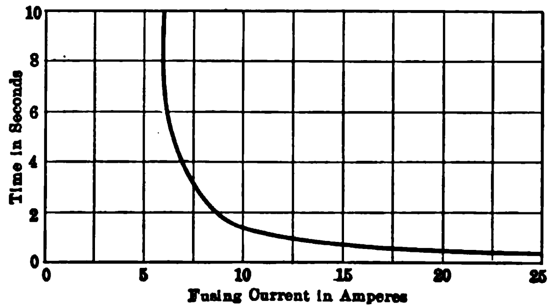

Fig. 135.—Time Characteristic for a No. 32, B. & S. Gage Copper Wire Fuse, 3 Inches Long

Fuses.—For protective purposes fuses are invaluable for some applications because of their quick action when a short-circuit occurs, a feature which is particularly important on high-voltage systems where the current to be handled is small and the large circuit breakers which would otherwise be used are slow in operation. The characteristic action of a copper wire fuse is shown in Fig. 135.

Circuit-Breaker Characteristics. — A small circuit breaker which is equipped with an instantaneous overload trip coil can be made to operate very rapidly. The trip coil itself will release the latch in less than one cycle when a heavy short-circuit occurs. The time required for a circuit breaker to open the circuit depends, of course, upon its size and the inertia of its moving parts, but for large capacity motor-operated or solenoid-operated circuit breakers having a rating of 15,000 volts or less it is between 0.2 and 0.3 seconds. The curves in Fig. 136 show the characteristics of such

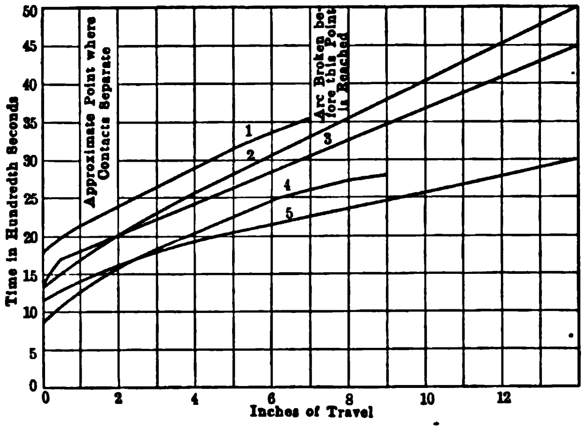

Fig. 136.—Typical Time Characteristics for Oil Circuit Breakers Showing Time of Opening Contacts with Various Types (1 = 15,000 Volts, 2,000 Amps; 2 = 88,000 volts, 300 Amps and 3 = 66,000 Volts, 300 Amps)

circuit breakers, although they may be altered materially if the operating voltage is low or the spring adjustment and other mechanical features are changed. Most of the time is consumed in energizing the trip coil and in overcoming the inertia of the moving parts, so that a 150,000 volt circuit breaker having a longer contact travel should not require much greater time to operate than is required by a low-voltage breaker.

Single Source of Power—Radial Distribution System.—The method of applying time-limit relays will first be considered for a distribution system having only one source of power supply.* Fig. 137 shows a radial system, which consists of a number of feeders leaving the generator bus-bars, each feeder being in turn subdivided into a number of smaller feeders. The smallest branches may be automatically disconnected from the remainder of the system by the blowing of fuses or the operation of instantaneous circuit breakers. The circuit breakers nearer the generator station are equipped with definite time-limit relays, the time interval between the successive relays being enough to insure a reasonable margin of safety above that required for the circuit breakers to operate. If, in addition to the variation in the operating of the switches, there is also an uncertainty in the operation of the relays, this time interval will become excessive, which emphasizes the importance of accurate relays. In addition to securing discrimination on the part of the relays by means of a definite time feature, it is also possible to discriminate by the current setting, because trouble which occurs at the far end of one of the branch lines will not draw as heavy a current as though it were near the generating station. There is also a possibility of securing selective action by using an inverse-time-limit relay having a characteristic curve similar to that shown in Fig. 138. If the calculations are carefully made this relay will operate properly and its use will enable heavy short-circuits close to the generator to be cleared sooner than they could be by the use of definite-time relays.

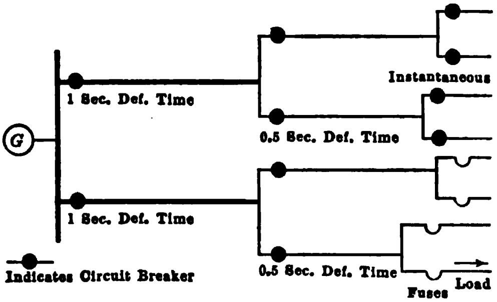

Fig. 137.—Layout for Radial Distribution System

When the inverse-time and the definite-time relay are combined so that they have the characteristic curve shown in Fig. 139, the combination is well adapted to this service, because either the inverse-time part of the curve or the definite-time part can be used, depending upon the conditions.

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* The systems of relay protection and layouts described in this and the following paragraphs are taken from an article in the July, 1916, *Electric Journal*, on "Use of Protective Relays on Alternating Current Systems," by L. N. Crichton.

Feeder Layouts.—Another simple arrangement of feeders is shown in Fig. 140 which illustrates a single generating station and substation connected by a number of parallel circuits. It has been frequently stated that such a system can be protected by the use of inverse-time-limit relays at the end of each feeder, and the success of these relays is supposed to be due to the fact that the particular circuit which is in trouble will draw a much heavier current than do its neighbors, with the result that the relay on the defective circuit will operate first. Experience has shown that this arrangement will not always operate properly. It will be seen by inspection

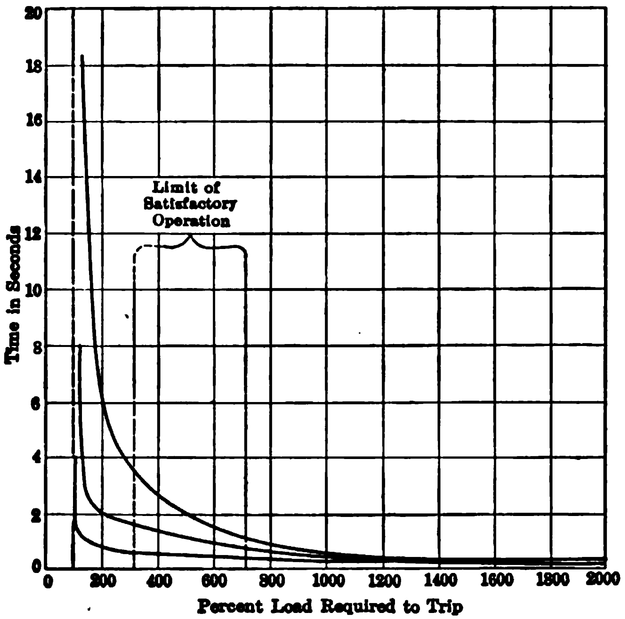

Fig. 138.—Time Characteristics of Bellows Overload Relay with Inverse-Time Limit

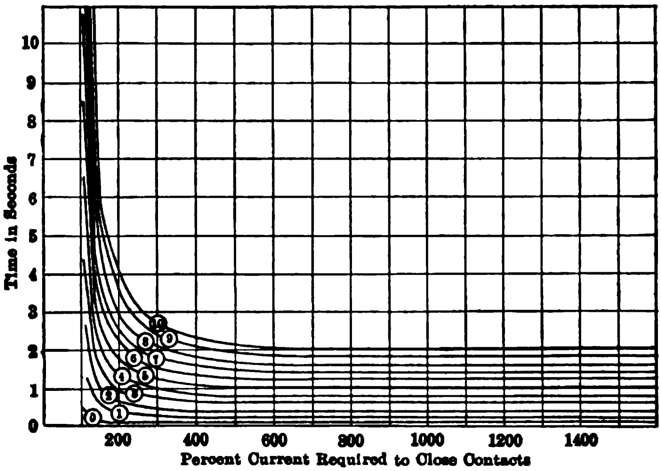

Fig. 139.—Time Curves of (Westinghouse) Definite Minimum Inverse Time Element Overload Relay—Numerals on Curves Indicate Time Setting

of Fig. 138 that the inverse-time-limit relay can be depended upon only between the limits of the two dotted lines. For greater current values it will not discriminate, because it is practically instantaneous, and for smaller values it requires such a long time to operate that a serious interruption would occur before a defective line could be disconnected. The result of such a limited range is that the relays cannot be adjusted to take care of all conditions when the connected generator capacity is changed. For instance, on a system having a load factor of 40 per cent., which is not unusual, the connected generator capacity at full load may be at least three times as great as the connected capacity at light load. Furthermore, the setting of inverse-time-limit relays is made difficult by the short-circuit characteristics of the generators. In Fig. 141 is shown how rapidly the short-circuit current of a generator decreases, and also shows how difficult it would be to approximate the effective values of this current when setting relays. Inverse-time-limit relays are thus shown to be impractical for protecting parallel feeders.

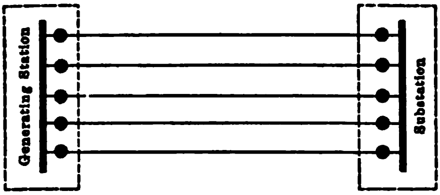

Fig. 140.—Layout of Parallel Feeders

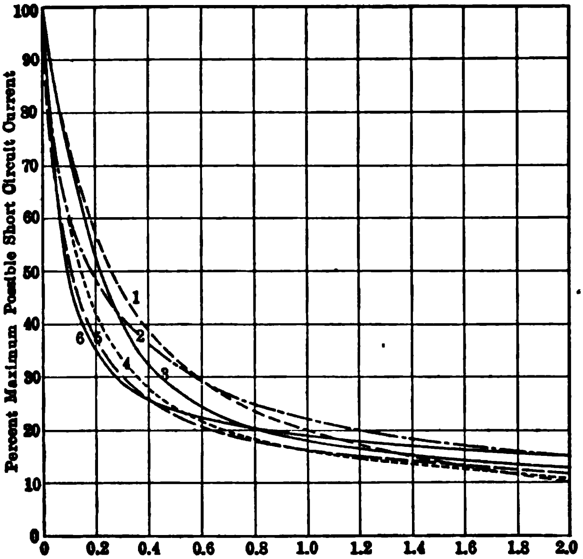

Fig. 141.—Current Decrease on Unsymmetrical Short-Circuits

	R. P. M.	Cycles	Phases Shorted
1—15,800 Kva. Turbo-generator	1500	25	3
2—20,000 Kva. Turbo-generator	1800	60	1
5—19,000 Kva. Turbo-generator	1875	62.5	1
3—12,000 Kva. Alternator	116	25	3
4— 6,600 Kva. Alternator	375	25	3
6—15,000 Kva. Alternator	375	50	3

The proper way to protect service against trouble on parallel feeders is to place reverse-power relays at the substation end of each feeder, and definite-time-limit relays at the generator end, as shown in Fig. 142. This figure shows a system consisting of a combination of parallel and radial feeders. Such a system may be simplified until it includes nothing but a generating station and a substation with two feeders connecting them.

Ring System.—The ring system shown in Fig. 143 is similar to the case of two parallel feeders supplying a substation, except that each feeder is made to loop through a number of substations. On such a system definite-time-limit reverse-power relays must be used, and the time limit of each successive relay should be increased by a sufficient amount to allow time for the circuit-breaker in the preceding substation to open. In the illustration it has been assumed that one-third second is a sufficient time to allow for this purpose, but such a small setting cannot be used unless the relays are accurate.

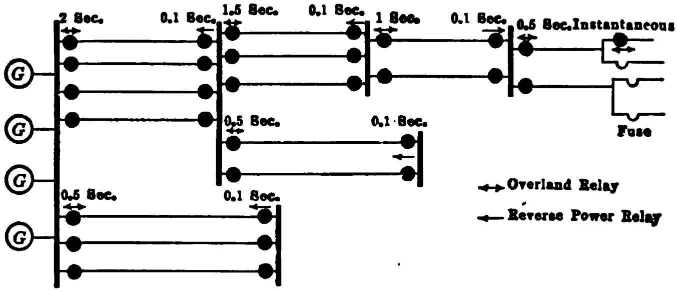

Fig. 142.—Use of Reverse Power and Definite-Time Limit Relays on Parallel Feeders

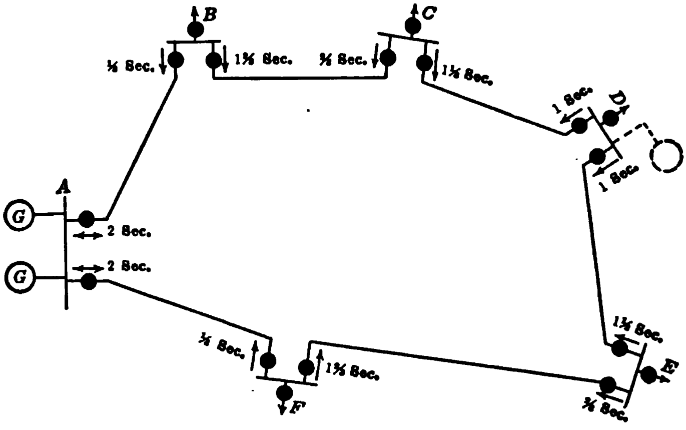

Fig. 143.—Relay Layout for Ring System

Systems Having More Than One Source of Power.—Such a system is shown in Fig. 143 with a generator placed at substation *D*. One difficulty would be encountered if the generator at *A* should be shut down and all the load carried by the generator at *D*. In this case the entire relay system would have to be readjusted, as shown in Fig. 144. Although this example is a simple one, it illustrates the condition which occurs whenever a complicated system of distribution is encountered. It also illustrates the necessity for using relays whose adjustment can be quickly changed.

Parallel Feeders.—When parallel feeders are used, reverse-power relays interconnected, as shown in Fig. 145, will give satisfactory service, irrespective of the direction of the normal flow of power. In this method the current transformers on the same phase of all the feeders are connected in series and each relay is shunted across its transformer. It is obvious that when the feeders are in good condition the current through the current transformers will be in the same direction in all of them and, as a result, very little current will flow through the individual relays because of their impedance. When one of the feeders fails, the current in it will be in the reverse direction to that of the others, or it will be much larger; in either case it will cause current to flow through the relay in the proper direction to trip the circuit breaker. The scheme must be used with caution because of the trouble which might occur if the current transformer leads have too much inductance or if the current transformer ratios are not adjusted to suit any difference which may exist in the impedance of the various cables. It is evident that if all the cables are not alike it will be necessary to correct for their dissimilarity by using current transformers

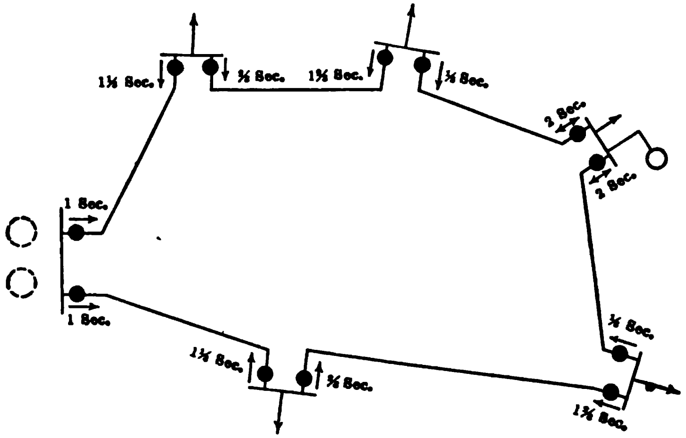

Fig. 144.—Relay Layout for Ring System Having More than One Source of Power

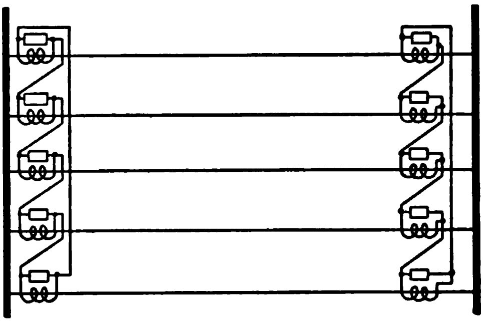

Fig. 145.—Protection for Parallel Tie Lines

having different ratios. When one of the feeders is disconnected it is necessary to short-circuit its current transformers, which can readily be done by placing a small pallet switch on the circuit breaker. This should be done even when there are only two lines, in which case a line will be non-automatic if it is the only one left in service. This scheme will fail upon occurrence of trouble which short-circuits one end of a feeder and leaves the other end clear. These objections are of slight consequence, and this scheme is the only one which can be satisfactorily used without requiring pilot wires, split conductors, or similar devices.

Networks.—The method just explained can also be applied to sections of a network such as is shown in Fig. 146. The difficulties which will be met with in protecting the duplicate feeders have already been considered and, for purpose of illustration, several other connections have been shown, although it is not to be assumed that these few examples cover all the problems which will arise in practice. In case of trouble, it is not always possible to prevent automatic switches from operating when the feeder which they control is not affected, nor is there any objection to opening a few such circuit breakers if they will not cause an interruption to part of the load. It frequently happens that the problem of automatic sectionalizing can be very much simplified if, at the first instant of short-circuit, a number of circuit breakers are opened for the purpose of simplifying the operation of the remainder of the system. In Fig. 146, for instance, is shown a feeder between substations N and S, which normally assists in maintaining voltage regulation, but which could be dispensed with for a time if there should be trouble on the line. We have, therefore, assumed that the circuit breaker on section A in the substation N is equipped with an instantaneous relay. If it should happen that the trouble is on this section of line, the relay in substation S will operate after one-half second, and clear the trouble; but

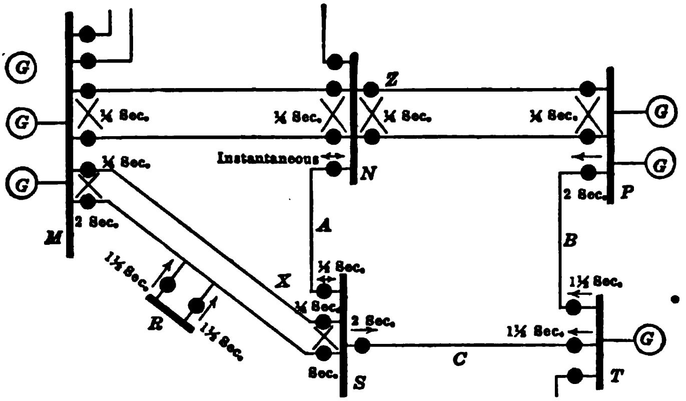

Fig. 146.—Network Distribution System and Relay Layout

if the trouble is not on this particular feeder no harm will be done and the load which is supplied from it will not be interrupted. In order that synchronizing and other switching on the system will not cause interruptions, it is assumed that the minimum time limit of one-quarter second is necessary. If such a setting is used, and a short-circuit occurs at the point *Z*, the relay in sub-station *N* will require one-quarter second to operate, and there will be a further one-quarter second required for the circuit breaker to open. The relays at substation *P* will not begin to operate until the switch at substation *N* has opened, because it is assumed that the short-circuit is close to the latter substation and there is, consequently, no unbalancing at substation *P*. There will, therefore, be still further delay of one-half second at substation *P* before the trouble is finally cleared. It is for this reason that the definite time limits in the tie feeders between substations *P*, *S* and *T* have been shown to be higher than appears necessary at first sight. With the setting shown in these substations it will require more than two seconds to clear a case of trouble should it occur in either section *B* or *C*. For this reason it may be thought advisable to adjust the relays at substation *T* so that they have a lower time setting, with the result that one of them will operate on practically all cases of trouble, but, as in the case of section *A*, this will not result in any interruption of service; it will merely trip out a circuit breaker which can later be closed by the attendant.

These illustrations show how to adapt relays to complicated systems, thus securing all the advantages which can be obtained from a close interconnection of stations and substations.

Pilot-Wire and Split Conductor Schemes—A number of years ago a pilot-wire scheme was proposed which operated from secondaries of current transformers placed at the two ends of a feeder and which, consequently, required that a number of conductors be run between the substations. For cable systems it is said to give satisfactory results, but for long-distance transmission lines it is not reliable. It ordinarily makes use of standard overload relays. The use of split conductors has been applied more recently, apparently with good results. This scheme is applicable only to cable systems, and consists in splitting each conductor into two parts, and using a relay which operates whenever the current in the two halves becomes unbalanced. A three-phase cable constructed on this plan contains six conductors instead of three, which not only increases the cost of the cable, but increases its size, thus requiring more investment in duct space. Although both the pilot-wire and the split-conductor schemes are reported to give satisfaction, there seem to be a number of conditions where failure is possible, and it does not appear that they can be any more reliable than the other schemes described.

Calculation of Short-circuit Current.—In applying any protective scheme it is necessary to determine the short-circuit currents which will be available under all conditions. It is unfortunate that the term "overload" has ever come into use in connection with sectionalizing distribution systems, because it implies that the relays should be set to operate at a value determined by the normal load on the feeder. Such a setting is possible if definite-time-limit relays are used, but where a relay having inverse-time characteristics is used it is necessary to consider the current which occurs during times of trouble, and which may be tens or even hundreds of times greater than the normal current. An approximate method of determining the possible short-circuit current is by observing the voltage drop between two stations at normal load.

$$\textit{Short-circuit current} = \frac{\textit{normal voltage}}{\textit{voltage drop}} \times \textit{load current}.$$

For example, if a certain load current causes a drop of five per cent. in voltage between a generating station and substation, the maximum short-circuit current would be 20 times the load current. Results obtained in this way are likely to be too large, particularly on lines having high inductance.

TABLE 45.—RESISTANCE, INDUCTANCE AND IMPEDANCE OF OVERHEAD LINES

Resistance (R)		Inductance X and Impedance Z Per Wire Per Mile							
Spacing—Ft.		2		4		8		15	
Size Wire	R	X	Z	X	Z	X	Z	X	Z
				25 Cycles					
0000	0.267	0.245	0.365	0.280	0.387	0.315	0.413	0.348	0.437
000	0.336	0.251	0.420	0.286	0.442	0.320	0.463	0.352	0.487
00	0.423	0.257	0.495	0.291	0.563	0.326	0.535	0.358	0.553
0	0.534	0.262	0.595	0.297	0.611	0.332	0.628	0.364	0.647
2	0.849	0.277	0.895	0.312	0.905	0.347	0.917	0.378	0.930
4	1.35	0.288	1.38	0.324	1.39	0.358	1.396	0.390	1.40
6	2.15	..	..	..	..	..	..	0.413	2.19
8	3.400	..	..	..	..	..	..	0.413	3.43
				60 Cycles					
0000	0.267	0.587	0.645	0.672	0.723	0.755	0.801	0.831	0.873
000	0.336	0.601	0.690	0.685	0.763	0.769	0.839	0.845	0.908
00	0.423	0.615	0.745	0.699	0.815	0.782	0.888	0.859	0.958
0	0.534	0.629	0.825	0.714	0.892	0.797	0.958	0.873	1.03
2	0.849	0.664	1.075	0.748	1.130	0.832	1.188	0.908	1.23
4	1.35	0.692	1.515	0.776	1.555	0.860	1.60	0.936	1.64
6	2.15	..	..	..	..	..	..	0.964	2.35
8	3.40	..	..	..	..	..	..	0.992	3.54

Above values are to be used with voltage to neutral. Sizes No. 0000 to 0 are stranded: others are solid. Based on 97 per cent. conductivity at 20 degrees C. or 67 degrees F. values in the Table were computed on slide rule.

The calculation of the short-circuit currents on a complicated system involves more or less approximation, and a good method is to prepare a table showing the impedance of each section of line and also of the generators. These figures can then be combined in any way desired to determine the impedance of a particular path. In obtaining the impedance of several sections of a system, the resistances and inductances must be added separately and the two sums combined vectorially. The inductance varies with the size of the conductors and with the distance between them, which in the case of a cable is determined by the thickness of the insulation. The characteristics of cables can usually be obtained from the manufacturers. A 15,000-volt No. 0000 cable at 60 cycles has an impedance about 23 per cent. greater than its ohmic resistance, whereas the impedance of a 150,000 volt line having the same size copper conductors spaced 15 feet apart is about three and one-quarter times the value of its resistance. The resistance, inductance and impedance of aerial transmission lines having various wire spacings is given in Table 45, and Table 46 shows the resistance and impedance of various kinds of three-conductor cable.

TABLE 46.—APPROXIMATE OHMIC RESISTANCE AND IMPEDANCE OF THREE CONDUCTOR CABLES, AT 60 CYCLES

Size	Resistance Ohms Per Mile	Impedance Ohms Per Mile					
		Working Voltage					
		3000	5000	7000	10000	15000	20000
2	0.850	0.858	0.859	0.863	0.867	0.872	0.884
1	0.674	0.692	0.696	0.700	0.706	0.712	0.724
0	0.535	0.545	0.547	0.552	0.558	0.565	0.580
00	0.424	0.436	0.439	0.444	0.452	0.460	0.478
000	0.336	0.352	0.352	0.357	0.365	0.374	0.396
0000	0.267	0.280	0.283	0.288	0.296	0.306	0.332
250000	0.227	0.245	0.245	0.252	0.261	0.272	0.299
300000	0.188	0.210	0.210	0.217	0.227	0.241	0.270
350000	0.161	0.187	0.187	0.194	0.204	0.217	0.250
400000	0.141	0.166	0.166	0.174	0.185	0.199	0.234
450000	0.127	0.148	0.148	0.156	0.167	0.182	0.221
500000	0.113	0.137	0.137	0.144	0.156	0.172	0.212

Based on pure copper, 75° F. with an allowance of three per cent. for spiral path of conductors, 60 cycles per second and standard thickness of varnished cambric insulation. Values are practically the same for other types of insulation. These figures are also approximately correct for 98 per cent. conductivity copper at 65° F.

The method of computing the impedance of a circuit, including a line, generator and transformer, is shown in the following example:

Assume:—A 5000 kva., 60 cycle generator having 10 per cent. reactance drop.
A 5000 kva. bank of transformers having one per cent. resistance drop and five per cent. reactance drop.
50 miles 45000 volt line No. 0 copper conductors spaced four feet apart.

All values of resistance, reactance and impedance will be reduced to terms of 45000 volts.

$$\text{Full load current} = \frac{5\,000\,000}{\sqrt{3}\times 45\,000} = 64 \text{ amperes}$$

Star voltage = 26,100.

Generator Characteristics:—

Reactance drop = 10 per cent. of 26,100 = 2610 volts

$$\text{Reactance} = \frac{2610}{64} = 41 \text{ ohms.}$$

Transformer Characteristics:—

Resistance drop = one per cent. of 26,100 = 261 volts

Resistance $= \frac{261}{64} = 4.1$ ohms

Reactance drop = five per cent. of 26,100 = 1305 volts

Reactance $= \frac{1305}{64} = 20$ ohms.

Line Characteristics (from Table 45):—

$R = 50 \times 0.534 = 26.7$ $\quad X = 50 \times 0.714 = 35.7$

Summary:—

	R	X
Generator	Negligible	41.
Transformer	4.1	20.
Line	26.7	35.7
Total	30.8	96.7 ohms.

$R^2 = 950$

$X^2 = 9150$

$Z^2 = R^2 + X^2 = 10,100$ $\quad$ Hence $Z = 100.5$ ohms.

The short-circuit current is therefore 26,100 ÷ 100.5 = 260 amperes for the first instant. As shown in Fig. 141, the initial current will decrease until the sustained value is reached. In this example the sustained value is probably about twice full-load current, or say 130 amperes. If the line should have more impedance, or if less generating capacity should be connected to the bus-bars, the generator reaction would have less effect in cutting down the current, and the calculated results would need less correction.

Alternator and Transformer Constants.—The characteristics of alternators vary through a wide range, but it is usually assumed that their reactance is about eight per cent., which allows a maximum instantaneous short-circuit current of 12.5 times full load. The maximum sustained short-circuit current is usually assumed to be between 2.5 and 3 times full-load, although some machines, particularly turbo-alternators, are now being built which have a sustained short-circuit current of about 1.5 times full load. It is usually safe to assume that a transformer has one per cent. resistance drop and five per cent. reactance drop.

Nature of Short-Circuits.—When making current calculations it should always be assumed that a short-circuit is due to a metallic connection between the conductors. On a high-voltage aerial line using wooden pins and cross-arms it sometimes happens that an insulator is broken, with the result that the wood is gradually heated by the passage of the current through it until it finally bursts into flame, thus causing an arc between conductors. A little consideration shows that the flow of current is small until the arc is established, and that it is absurd to speak of automatically disconnecting a section of line which has such a high-resistance short-circuit. It has sometimes been assumed that an arc has a high resistance, but this is not the case, and in general the presence of an arc at the point of short-circuit will not decrease the short-circuit current by more than a few per cent. Incidentally, it may be of interest to note that on a high-voltage, ungrounded-neutral system the capacity current to ground through an arc is greater than it is through a direct ground. There is only one case where a short-circuit is likely to increase in intensity as it develops, and that is on a system where the neutral is grounded through a resistance; a cable break-down, for instance, frequently occurs first between one conductor and the sheath and the current flow may be limited by the neutral resistance; the trouble will quickly involve all the conductors in the cable, resulting in a heavy short-circuit, but it is possible that it will require an appreciable time to do this, in which case the relay operation may be unsatisfactory. This is particularly liable to happen if the neutral is not grounded at every substation.

Relay Accuracy.—A study of the preceding discussion will show the necessity for the use of relays which are not only accurate and constant in their characteristics, but can also be adjusted to operate on small differences of time. When the relays are individually adjusted and have the calibration curve marked on the nameplate it is possible to set the relay to the desired value with only a few minutes work. The relay, having combined definite and inverse-time characteristics, is particularly valuable on large systems where constant changing of the connections necessitates frequent changes in the relay settings.

Effect of Low Voltage.—The most important requirements of a reverse-power relay is that it should operate when the potential at its terminals is between one and two per cent. of normal. If we assume the case of a No. 0000 cable normally carrying 300 amperes at 12,000 volts, connected to a generating station having a short-circuit current of 3000 amperes, the loss which would occur between the bus-bars and a metallic short-circuit 100 feet from them would be 45 kw. per phase, or less than three-quarters of one per cent. of the relay setting. This shows the absurdity of installing relays which require a percentage reversal of five or ten per cent. to operate them. The proper way to construct a reverse-energy relay is to use two elements, one of them an excess current element which may be equipped with any time limit desired, and a selective watt element which is sensitive enough to indicate accurately which direction the power is flowing in the circuit, even at the lowest possible value of voltage. The co-operation of both elements is necessary in order to trip the circuit breaker. The statement has frequently been made that a reverse-power relay cannot operate when there is no voltage, but neither can there be a flow of current unless there is a difference of potential. The problem is therefore nothing more than a question of securing a contact-making wattmeter which is sensitive enough to operate on the small potential which is always present when a short-circuit occurs. The potential drop across the arc at the point of short-circuit, although small, is in itself sufficient to operate inverse time element overload and reverse power induction relays. Numerous tests have been made which show that when a cable breaks down, the arc through the insulating space between conductors will maintain a voltage of between one and two per cent., and it has been found that a higher voltage is maintained when the current is small than when it is excessive, a fact which materially assists reverse-power relays. It should be pointed out that on large systems it is practically impossible to obtain a metallic short-circuit because any small object which could be brought into contact with the bus-bars would be immediately destroyed. The only possibility for obtaining a short-circuit which will lower the voltage to a point where reverse-power relays cannot operate is the case of an extra high-voltage system where the short-circuit current is so small that it cannot burn off a metallic connection. For instance, on a 150,000 volt system of some magnitude, the current at short-circuit may not exceed 500 amperes, which could be carried for some seconds by a telephone wire dropped across a transmission line. The possibility of interruption from this cause is remote, because a short-circuit across three wires will not often occur, and when only two wires are involved the low-voltage condition does not exist except on one phase.

Effect of Unbalanced Short-circuits.—In the past the operation of reverse power relays has been somewhat unsatisfactory, because means were not taken to insure correct operation at times when the power-factor of the system was bad, due to unbalanced short-circuits. As a result of several years' investigation, it has been found that the method of connecting reverse-power relays with their potential coils in star, as has been the usual custom, is theoretically incorrect, and the relays will fail to operate upon the occurrence of the most common form of short-circuit. When unbalanced short-circuits occur, a large number of combinations of circumstances are possible, but it has been found that the most severe condition is when only two conductors of a three-phase line are short-circuited, and if relays will operate properly under this condition they will satisfy practically all the others.

In Figs. 147 and 148 are shown in a rather incomplete way the vector relations on a simple electric circuit when a short-circuit occurs between the wires B and C. Fig. 147 shows at a the voltage triangle at the generating station and at b the voltage triangle some distance from the generating station. At c is represented the conditions at the short-circuit, and it will be seen that the long sides of the voltage triangle have closed in together. It will also be observed that the two star voltages, OB and OC, are in phase. Referring again to a, if the circuit has no inductance, the current which flows into the short-circuit will be in phase with the voltage BC, as is shown by the vectors I_B and I_C. If such a condition were possible, none of the relays at the short circuit could operate, because the power factor is zero. Since, however, there is always inductance in the circuit, the current will lag somewhat, as shown by the vectors I'_B and I'_C. The result of this is to cause one of the relays at the short-circuit to operate forwards and the other one to operate backwards. Fig. 148 shows the effect of an inductive load on the system. The short-circuit currents are shown by single prime vectors, and resultants of the short-circuit currents and load currents by double prime vectors. The result of the load current on the system is to make less pronounced the effect due to the short-circuit, as will be observed upon comparing *b* in Figs. 147 and 148. In the former case one of the relays operates backwards, but in the latter case both of them read properly.

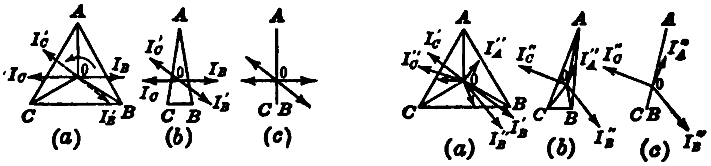

Fig. 147 Fig. 148

Figs. 147 and 148.—Vector Relations for Short Circuit on an Unloaded Circuit and on a Loaded Circuit

In the above explanation, the condition in only one line has been shown, and the question might immediately arise as to what difference it makes whether or not one relay operates backwards, so long as one of them operates to trip the circuit breaker. The answer is that the same condition exists in all the good sections of line adjacent to the trouble, with the result that their circuit breakers will also be opened.

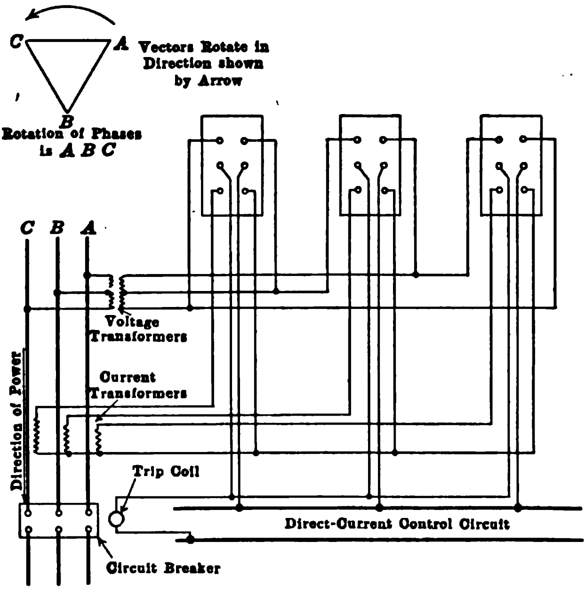
C
A
B
Vectors Rotate in Direction shown by Arrow
Rotation of Phases is A B C
C B A
Voltage Transformers
Current Transformers
Direction of Power
Trip Coil
Direct-Current Control Circuit
Circuit Breaker

Fig. 149.—Connections of Relays to Cause the Current to Lead the Voltage on Non-Inductive Loads

One method of curing this trouble is very simple. Since the distorted condition is due to a single-phase being short-circuited, the relays should be connected with the potential coils across the same conductors which are causing the short-circuit. In other words, the potential coils should be connected in delta in accordance with Fig. 149. Because the current will lag behind the voltage when a short-circuit occurs, the connection should be so made that at unity power-factor the current in the current coils of the relays will lead the potential by 30 degrees. This connection not only overcomes the trouble from distortion, but it allows the relays at all times to operate under a higher power-factor. In order to make this connection satisfactory it is necessary to take into account the direction of the rotation of phases.

The above discussion is not based solely upon the mathematical study of the problem, but is the results of actual tests made on a number of transmission lines where the reverse-energy relays connected according to the old method have not given satisfactory service. Experiments have shown that this method of connection should also be used on systems having a grounded neutral. This connection (with the current 30 degrees ahead of the voltage) must be used with care on an ungrounded neutral system having a heavy charging current to ground. Difficulty may also be encountered on some systems where the load current is leading. But in both these cases the short-circuit currents will be much greater than any possible leading current and no difficulty due to incorrect operation of the reverse-power relays will be experienced if the excess-current elements are adjusted to operate only on short-circuits.

Overload and Reverse-Current Relays.—Various manufacturers have in the past made a type of relay which would operate on a heavy overload in either direction and would also operate on a small overload in reverse direction. Such a relay is occasionally desired for the purpose of limiting the amount of power which can flow into a piece of apparatus, but it is not satisfactory for line sectionalizing and its manufacture has been almost abandoned. The principal objection to it is that its operation cannot be foretold when unbalanced short-circuits occur.

Current Transformers Required.—To insure satisfactory protection on a grounded neutral system, current transformers should be placed in each wire, and it is advisable to do the same on an ungrounded neutral system. This is because two conductors in different phases of different sections of line are likely to be grounded simultaneously, thus resulting in a short-circuit which involves two line sections. For instance, suppose that phase *A* in one section of line becomes grounded and the resulting surge in voltage causes a breakdown in another section of line in phase *B*. If both of these wires should happen to be without current transformers, the short-circuit could not be cleared. This is not a fanciful example, but is one which occurs quite frequently on overhead lines, due to the simultaneous flash-over of two or more insulators. Even if no such trouble is feared, there is an advantage in using three current transformers and three relays at every switching point, because by such means additional insurance is provided against the failure of any one relay to operate. This applies particularly to reverse-power relays under conditions where only two wires are short-circuited, because then one of the relays is operated under very low voltage.

Potential Transformers Required.—Two potential transformers connected in *V* are sufficient to operate three reverse-power relays. On high-voltage systems it is sometimes inconvenient to connect potential transformers on the line side of the power transformers, in which case they may be connected to the low-voltage bus-bars. If the power transformers are connected star-delta, the potential transformers should be connected the same way in order to bring the phases into the proper relation.

Special Protection for Apparatus.—*Transformers.*—In general, the current which can flow through rotating apparatus is limited to a reasonable value, and quick action in disconnecting such apparatus from the system is not essential. Transformers having low internal reactance are quite likely to be damaged in a few seconds if they are short-circuited, and a means of protecting them against internal short-circuits is shown in Fig. 150. The current transformers in the corresponding primary and secondary leads have their ratios so chosen that the current is equal through both secondaries. The normal current, therefore, circulates through the two transformers and does not pass through the relay because of its impedance. If a short-circuit occurs in the power transformer, the current through the current transformers will be reversed in direction so that it cannot circulate through them, but will flow through the relay and cause it to operate. It is possible that the ratio of the power transformer may be such that standard current transformers placed in its primary and secondary will not have equal secondary currents, in which case the difference between the two currents will flow through the relay. There is no particular disadvantage in this if the relay is given a sufficiently high current setting.

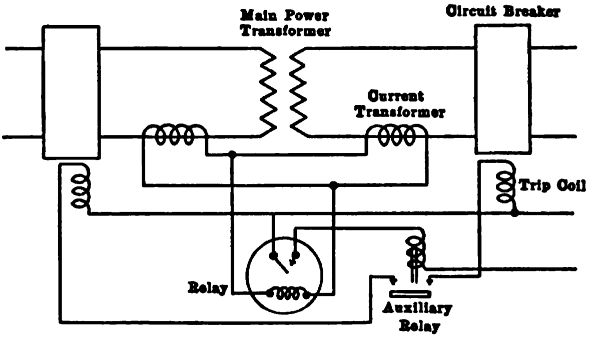

Fig. 150.—Protection Scheme for a Transformer

Generators.—Where generator protection is necessary against the extensive damage which will occur before a short-circuited generator can be disconnected by the operator, a scheme for connecting balanced current-transformers (Fig. 151) similar to that shown in Fig. 150 may be employed. It will protect against occurrence of short-circuits in the generator windings or in the leads, and it will not introduce any risks of disconnecting the generator upon the occurrence of an overload; but it has the objection of requiring the opening of the generator winding at the neutral point, which is often difficult, and it cannot well be applied to delta-connected machines. It is believed that satisfactory protection can be obtained against generator failures by installing reverse-power relays to operate on a current slightly less than the sustained short-circuit value of the generator and with a definite time-limit of say one-half second. This will not disconnect the generator upon loss of field if it is carrying load, although it might disconnect it if it is unloaded.

Motors.—The protection of motors has been thoroughly standardized, the only doubtful feature of existing practice being the often unnecessary use of the low-voltage release; a short-circuit on a distribution system frequently lowers the voltage at a sub-station to such a value as to have

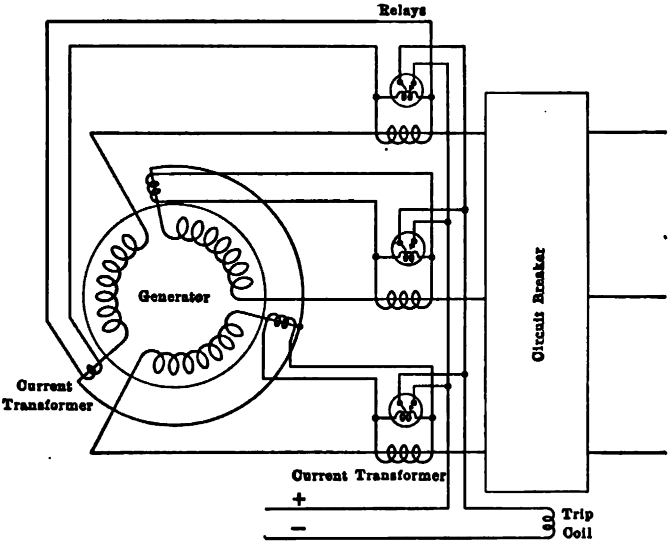

Fig. 151.—Protection Scheme for a Generator

the same effect as an interruption. If the system is properly sectionalized, a short-circuit should be cleared within three seconds, and practically any motor load will withstand such a disturbance without inconvenience. It is therefore obvious that the use of a device which will instantly disconnect a motor when the voltage falls to a low value does not assist in maintaining continuous service. It is better practice to equip the low-voltage release with a short time-limit, or to omit it entirely and depend upon an overload device for protection.

The effect of a short-circuit on a distribution system should also be considered when adjusting the overload device on a motor. When an unbalanced short-circuit, such as has been previously described, occurs on a system, all motors, both synchronous and induction, attempt to maintain a balanced voltage on all three phases. A motor under such conditions will receive power from the good phases and send it back into the line over the bad phase, with the result that the current in all three wires is excessive. Overload protective devices on motors should therefore have sufficient time limit to allow the sectionalizing circuit breakers on the distribution system to clear the trouble before the motors will be disconnected.

Protecting Three-Phase, Star-Delta Transformers.—A three-phase bank of star-delta transformers, having a grounded neutral, acts in a manner similar to an induction motor in that it attempts to maintain the voltage equal on all three phases. As a result, if a ground occurs on the distribution system, the star-delta transformers will supply current to the grounded wire, irrespective of whether these transformers are at substations or generating stations. In other words, if a small bank of transformers is connected to a large system, and has its neutral grounded, it will be subject to short-circuit conditions every time there is a ground on the distribution system. For this reason banks of small transformers should have their neutrals isolated, not only because of the strain which frequent short-circuits throw on them, but also because of the service interruptions.

The above argument applies principally to high-voltage systems, but it is necessary to consider the same conditions on a low-voltage four-wire system. Four-wire systems are usually used when a large amount of single-phase load is to be distributed, and as a result the voltage on the three phases is liable to be unbalanced. When a bank of delta-star transformers is connected on to such a system, the question of grounding the neutral must be carefully considered. As a rule, it is dangerous to make such a connection if the transformers are small, but if they are large it may be advisable to utilize them to assist in maintaining balanced voltage. The balancing is effected by drawing current from the high-voltage phases and supplying it to the low-voltage phase, with the result that there is a flow of current through the neutral connection. The possibility of burning out the transformers can be prevented by installing an overload relay in the neutral connection and connecting it so it will sound an alarm or automatically open the neutral.

It frequently happens that star-delta transformers are connected to the main circuit through fuses, and trouble is encountered when a single fuse is opened. If the transformer neutral is ungrounded, the load will operate single-phase, with the possibility of injuring the motors. On the other hand, if the neutral is grounded, two of the transformers will carry all the load at a much lower power-factor than normal. Usually there is no way of knowing that the fuse is blown, with the result that the transformers will continue to carry the overload until they are destroyed. A relay installed in the neutral and arranged to give an alarm seems to be the best means of preventing the transformers from being damaged.

Protecting Small Substations.—It sometimes happens that a substation is supplied by duplicate feeders which are equipped with reverse-power relays to operate in case of line trouble, and it is desired to install overload relays which will open both circuit breakers in case of trouble on the sub-station bus-bars. This can be done by installing overload relays in series with the reverse-power relay, but the time setting must be sufficiently high so that the operation of the reverse-power relays will not be interfered with. A further disadvantage is that the setting of the overload relays must be changed whenever one of the lines is disconnected if it is desirable to maintain the same degree of protection. Both these objections can be overcome by installing an overload relay in such a way that it is operated by the total current flowing into the substation in the manner shown in Fig. 152.

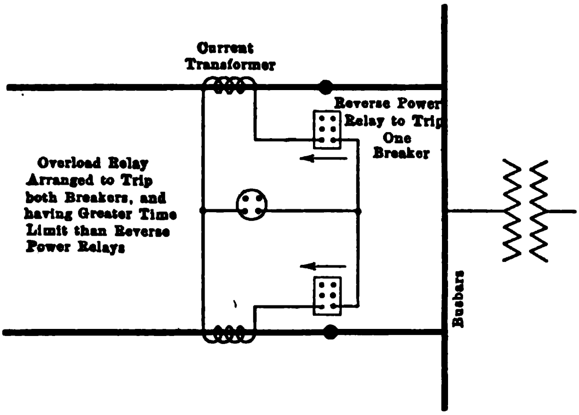
Current Transformer
Reverse Power Relay to Trip One Breaker
Overload Relay Arranged to Trip both Breakers, and having Greater Time Limit than Reverse Power Relays
Busbars

Fig. 152.—Protection for a Substation Supplied by Duplicate Line

Details of Relay Construction.—*The Plunger Type* of overload relay, although widely used for simple applications, such as the protection of motors, is not adapted to the accurate work required in automatically sectionalizing distribution networks. Some of these relays now on the market have received a bad reputation because of their poor workmanship and design. One difficulty is that the continuous vibration to which they are subjected gradually loosens the set screws and other parts, with the result that they fail to operate at a critical time. It must be remembered that the force on the plunger increases as the square of the increase in current, with the result that the forces reach enormous values when heavy short-circuits occur. It is, therefore, no uncommon thing for relays of this type to be so seriously damaged by a heavy short-circuit that they will not operate when another, milder short-circuit occurs.

Bellows Type.—The plunger type relays which depend upon a bellows for their time limit are unsatisfactory, because an extreme short-circuit compresses the air in the bellows until contact is made, and then at the zero point in the current wave, when the force on the plunger is released, the air in the bellows expands and opens the contact. This "chattering" not only causes the contacts to be badly damaged by the arcing, but delays the opening of the circuit breaker. The definite-time relay is usually so designed that, when the core is lifted, it compresses a spring which, in turn, acts upon the bellows. After the core has been lifted, the current required to hold it in the raised position is much less than that required to lift it, with the result that the relay will not reset until the overload has decreased to a current much smaller than the tripping value.

Oil Dash Pot.—The plunger-type relay, having an oil-filled dash pot as its time-limit device, cannot be used for automatic sectionalizing because of the great change in the viscosity due to changes in temperature.

Expense of Adjustment.—An objection to the use of all such relays is that the expense of adjusting them for accurate work is oftentimes greater than the cost of the relays themselves. It is possible that an automatic sectionalizing scheme could be so laid out that time limits varying by steps of one to two seconds could be used, in which case the bellows type of relay might be sufficiently accurate, but such accuracy could not be obtained except at considerable expense. In order to adjust relays of this type it is necessary to disconnect them from the circuit and connect them to a test circuit which, in many cases, is not easy to obtain. In addition, a chronograph, ammeter and control device are necessary. Needless to say, such a calibration must be made by a skilled tester. If a change in the time limit is later required it is necessary to repeat the entire process.

Induction Type.—The best feature of the induction type of overload relay is its remarkable accuracy and permanence of calibration. The use of permanent magnets as a time-limit device prevents over-swinging and chattering of the contacts, and the construction is such that the relay will instantly cease its movement when the overload disappears. There is no possibility of mechanical injury due to excessive currents when the torque compensator is used, because the saturation of the iron prevents the mechanical forces from increasing beyond a certain amount.

Ease of Adjustment.—The current and time adjustments of the induction inverse time element relays are plainly and accurately marked and any desired change can be made at a moment's notice. This is a feature much appreciated by the operating man who is responsible for the successful operation of the automatic sectionalizing devices on his system. He can personally check the setting of every relay and thus be sure that no incorrect operation will result due to the carelessness or incompetence of an assistant.

Relay Contacts.—One difficulty in relay operation which requires consideration is that which occurs due to the burning of the contacts when heavy tripping currents are handled. The tripping circuits are, as a rule, highly inductive, and an arc which would be formed due to opening such a circuit will persist for a considerable length of time, and thus cause an unnecessary amount of burning on the relay contacts. For this reason it is necessary that the tripping circuit be opened by an auxiliary switch fastened to the circuit breaker in such a way that the opening of the circuit breaker automatically opens the tripping circuit. It sometimes happens that large circuit breakers require a much heavier current to trip them than can safely be carried by the relays. This difficulty is overcome by the use of an auxiliary relay switch which is operated by the protective relay and which closes the tripping circuit of the main circuit breaker. A relay switch is also used when it is desired to trip several circuit breakers from one relay.

Series Tripping.—The usual method of tripping circuit breakers is by means of a trip coil operated by direct current, and for this purpose relays known as "circuit-closing" relays are used. Where a source of direct-current power is not available it has been customary to use "circuit-opening" relays which normally short-circuit the trip coil of the circuit breaker—when the relay operates; it opens this short-circuit and allows current from the current transformer to energize the trip coil. In theory this scheme operates very nicely, but in practice it has been found that the short-circuiting device is quite likely to develop a high resistance in its contacts, which will cause the trip coil to operate when there is no occasion for it to do so. Up to the present(1916) no satisfactory circuit-opening protective relay has been placed on the market, a statement which can easily be proved by referring to the changes which manufacturers are continually making in the design of this type of relay. All the difficulties which occurred with the circuit-opening relay have been overcome by the development of the "direct-trip attachment," which utilizes current from the current transformer to trip the circuit breaker, but which operates with a circuit-closing relay.

Load on Instrument Transformer.—When selecting a relay for use on current transformers which also operate instruments, it is important to consider the load which the relay places on the transformer. The induction type of relay requires a smaller amount of energy than does any other type, a feature to be appreciated when bushing-type current transformers are used. When transformers of this type are heavily loaded their ratio is not constant and there is also a noticeable difference in phase between the primary and secondary current. Reverse-power relays such as the Westinghouse adjustable definite minimum inverse time element design require such a small amount of energy that the phase angle error will not be great enough to affect their operation even if they are used on bushing-type current transformers having a small ratio of transformation.

Convenience in Testing.—In selecting a reverse-power relay it is not only important to obtain one having satisfactory operating characteristics, but the question of convenience in checking its connections must be considered. If the relay is a sensitive one, it can be tested by feeding a small amount of power through it in the reverse direction. On some systems the power loss in a bank of transformers located on the line side of the relays may be sufficient to cause their selective elements to operate backwards and thus test their reliability. On the other hand, a relay which requires five or ten per cent. reversal of power in order to operate it cannot be tested except at great expense, and it is usually necessary to determine by more or less costly experience whether or not the relays are connected backwards.

Transmission Line Economics.—Conductors in long distance transmission lines constitute the largest item of investment and directly affect the kilowatt-year loss of energy, that is, the value of energy lost in transmission continuously. As a decrease in investment demands an increase in the cost of power station apparatus, etc., producing the extra energy lost in the line (and probably, operating expense), it is evident there must be a point where the cost of conductor material and cost of lost energy will cross, that is, be of equal value. Since every conductor dissipates a certain amount of energy the most economical size will depend upon the cost of producing energy. If operating expenses are low, much energy may be economically wasted. If, however, they are high, more conducting material must be used in order to reduce the amount of the energy wasted. It is possible that operating costs may be so low that a purely economic consideration may indicate a conductor so small that it would become unduly heated, consequently the minimum conductor-section should be that which will provide such an area as may be safely and continuously operated.

The problem confronting all practical engineers responsible for the design and economical operation of power transmission systems is, the choice of the most economical size of conductor for a given case. The operating manager is directly interested in the value of the electrical energy lost per year in transmission, and also in the interest cost on the investment of transmission lines, that is, the total annual cost of transmitting a given amount of energy. For a definite amount of power to be transmitted, and a definite voltage, the current can be calculated and the economical conductor cross-section obtained; therefore, the weight and cost of the conductor will be proportional to the current.

Most Economical Conductor.—*Kelvin's Law.*—By Kelvin's law it can be shown that the most economical area of conductor is that for which the annual cost of wasted energy is equal to the annual interest on that portion of the capital outlay which can be considered to be proportional to the conductor resistance, independent of the voltage and the distance of the transmission line. It can also be shown that, if the ratio of the selling price of electrical energy to the direct cost of generating the energy is P_r, the ratio of the actual economical investment in conductor to the apparent economical investment in conductor, is

$$C_r=\sqrt{\frac{3P_r-1}{2}}$$

where P_r is the ratio of the selling price of energy to the cost of generating the energy, and C_r is the ratio of the actual to the apparent economical investment in copper conductor.

Graphical Application of Kelvin's Law.—There exist several ways of treating Kelvin's law by means of graphics. Graphical treatment is the most simple particularly when plotted in terms of per cent. values. The most important methods of treating Kelvin's law are, in a sense, identical in that they do not in a single instance change the position of the curves or values. The three different factors involved are fixed charges, weight and resistance. The exact position of the curves and values based on these treatments do not change for any of the following methods:

(a) Relative cost of line losses to relative investment in line conductor, or, ratio of fixed charges to the cost of line losses.

(b) Ratio of line conductor cost to values proportional to the weight of conductor.

(c) Ratio of line conductor ohmic resistance to values proportional to the cost of conductor.

Method (a) is of special importance because it takes up a combination of the complete technical as well as the commercial side. Methods (b) and (c) differ in no essential points as the weight of a conductor is proportional to its ohmic resistance, and vice-versa.

Let it be supposed that with an investment in copper, the cost of energy wasted in the line (P_c) amounts to a given per cent. per year. Also suppose that with this investment the fixed charges (C) as interest, taxes, depreciation, etc., are equal to cost of energy wasted with that investment in copper. Then, the total yearly expense will be

$$T_c = P_c + C$$

Suppose the copper was increased to $2P_c$, then the line losses would be decreased 50 per cent., or

$$T_c = 2P_c + 0.5C$$

But if the investment in copper be reduced to one-half, the line losses will be increased two-fold, making

$$T_c = 0.5P_c + 2C$$

Take for example an investment of $50,000 in copper, and assume the cost of energy wasted in the line to be 20 per cent. per year, or $10,000. Also assume the fixed charges (interest, taxes, depreciation, etc.) to amount to 20 per cent. per year, or an amount of $10,000 equal to the cost of energy wasted. The total yearly expense will be,

$$T_c = 10{,}000 + 10{,}000 = \$20{,}000:$$

With a two-fold increase in copper investment the total yearly expense would amount to,

$$T_c = 20{,}000 + 5{,}000 = \$25{,}000:$$

If the copper investment in the line were reduced one-half, the total yearly expense will become,

$$T_c = 5{,}000 + 20{,}000 = \$25{,}000 \text{ (as before).}$$

In these cases no consideration has been given to a change from losses in the line to energy sales, nor is the extra energy generated and sold item provided for. Let the change from line losses to energy sales be K and the extra energy generated and sold be k, then, for a given case we have

$$k = \frac{P_c}{2}$$

and the total increase in energy sales becomes,

$$T_s = k + K = 3k$$

with a gross profit of

$$G_p = 2T_s$$

the final expense is,

$$N_c = T_c - G_p$$

Let us now assume a double investment in copper of $100,000, which will result in correspondingly increased fixed charges on conductor or $20,000. The increase in copper has, however, consequently cut the line losses in half or to $5,000, so that the total annual expense is $25,000. Now, the saving of $5,000 in the cost of line losses due to the two-fold expenditure in copper conductor, should correctly be added to energy sales at existing sale prices. Also, allowance should be made for the extra energy generated and sold at existing sale prices, or

$$k = \frac{5{,}000}{2} = \$2{,}500:$$

Hence, the total increase in energy sales per year not accounted for by Kelvin's law, is

$$T_s = 5{,}000 + 2{,}500 = \$7{,}500: \text{ per year}$$

The net annual expense due to copper has been reduced to

$$N_c = T_c - G_p$$

or taking G_p as $2T_s = \$15{,}000$: we have

$$N_c = T_c - G_p = 25{,}000 - 15{,}000 = \$10{,}000: \text{ net expense.}$$

It is therefore observed in this case that when the power company can sell energy at a price three times the increment cost of generation, the most economical investment in copper is twice as much as the amount that would be indicated by the use of Kelvin's law. Of course, the selling price of electrical energy per hp. is much more than three times the cost of its generation in the majority of cases, but this example has been given to show just how the comparison on this basis is directed. No account has been taken of the fixed and variable costs of such items as poles, towers, insulators, insulator-supports, etc., as these should at all times be considered separately. Any practical variation in the line (size of conductor) will not, generally speaking, have any effect on these costs. Thus, from the above it would seem that the law laid down by the late Lord Kelvin (Sir William Thompson) would be better expressed in the form: *When the total cost of conductor in the line is equal to the cost per kw.-year to the company of the energy wasted, the most economical conductor cross-section is obtained.*

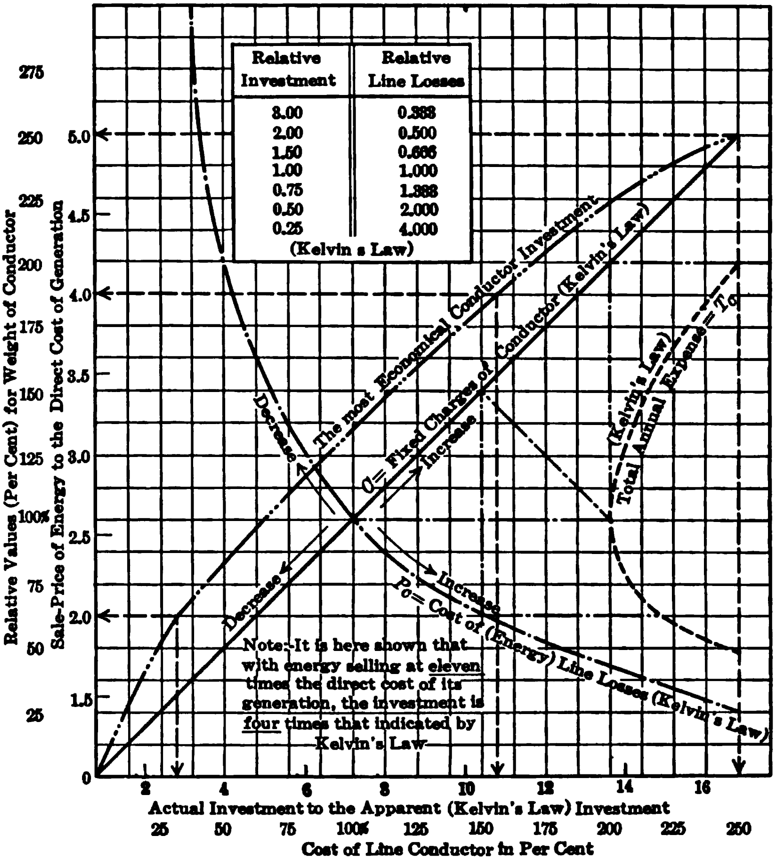

Fig. 153.—Relation Between Copper Investment and Cost of Line Losses

The use of this law as given in Fig. 153 is greatly aided by a set of curves giving amperes per phase in terms of line voltage and kilowatts such as shown in Fig. 154. Since the three-phase system of transmission and distribution is so much in general use these curves should be of practical value. They are based on the following formulæ,

$$P=\sqrt{3}EI \text{ and } I=\frac{P}{\sqrt{3}E}$$

Ferranti Effect in Transmission Lines.—Very long transmission lines connected to the supply service at the generating end but open-circuited at the far off receiving end, tend to maintain a higher voltage at the latter point (receiving end). This condition is commonly called the Ferranti effect from its having been first reported by Dr. S. Z. de Ferranti in London a quarter of a century ago. At present day power-transmission frequencies (not exceeding 60 cycles), the quarter-wave length of line is so great that it is not approached on the longest transmission line in service; but the higher the impressed frequency the shorter the quarter-wave length. The Ferranti effect of a long power-transmission line may be about 1.0 to the fundamental frequency—taking the natural period at,

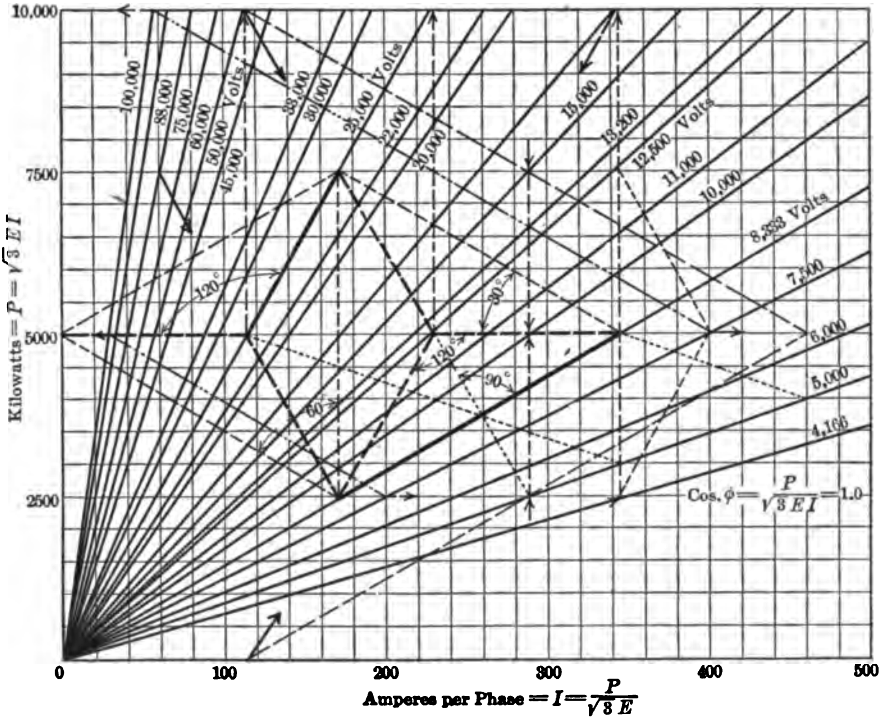

Fig. 154.—Values of Amperes per Phase in Terms of Line Voltage and Kilowatts

$$f = \frac{1}{4\sqrt{LC}}$$

or a quarter-wave of 363 cycles, but a relatively small high-frequency ripple in the wave of the generated voltage may increase this factor to about 1.5 or even more. It, therefore, becomes of importance to know how large the Ferranti factor may become with frequencies which may present themselves as harmonic ripples in the voltage wave of generators. Experience tends to show that there is no better system of connections for long high-voltage transmission lines than generators in star with step-up power transformers in delta-star and the step-down power-transformers in star-delta-connection —star on the high-voltage side in each case.

Line-voltage Limited by Corona.—For transmission lines the line-voltage is limited in one way by the phenomenon of corona. The loss of power (p_c) due to corona may be approximated from the formula, by Peek.

$$p_c = 1.61\,\frac{k}{\delta} f \sqrt{\frac{r}{S}}(e-e_o)^2 \times 10^{-5}$$

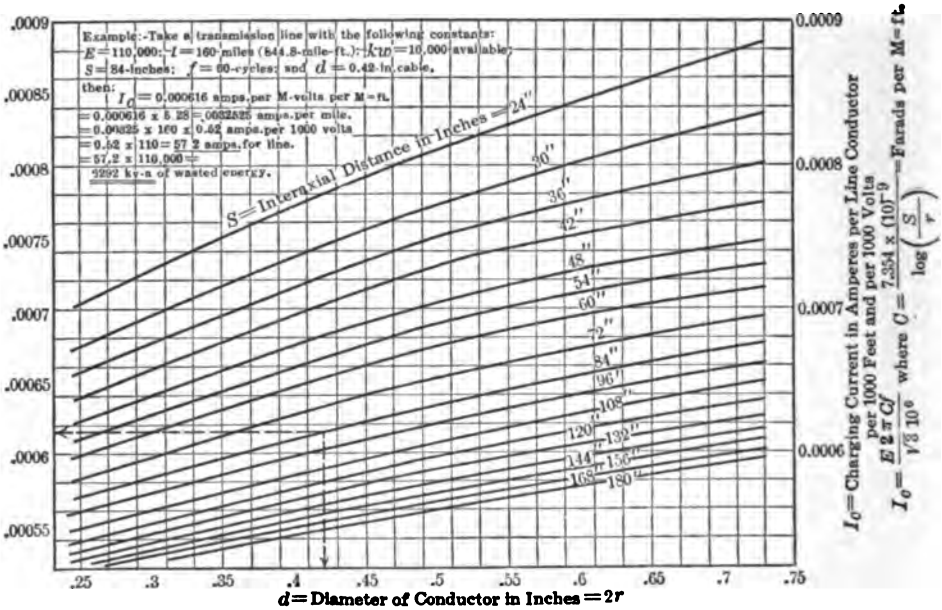

Fig. 155.—Curves Giving Charging Current in Amperes for Varying Values of Conductor Spacing, Diameter, Voltage and Length of Conductor Suitable for Three-Phase, 60 Cycle Transmission Lines

For very heavy lines, with large reactance, or where the cost of power for line losses is low, the theoretical limit for constant-voltage lines may be approached, which, of course, will involve increased cost of synchronous condensers. The load limit for a line operating at constant voltage by means of synchronous condensers is much greater than that without synchronous condensers, and the limiting condition is usually low efficiency.

The charging current, expressed as

$$I_c = \frac{2\pi f C E}{\sqrt{3}\ 10^6}, \text{ capacity current}$$

$$C = \frac{7.354 \times (10)^{-9}}{\log \frac{S}{r}} = \text{Farads per M-ft.}$$

is of small commercial importance, even though it may be large in amount, and must be carefully allowed for. Its main advantage is that it increases the voltage rise when load is suddenly disconnected from systems not closely regulated.

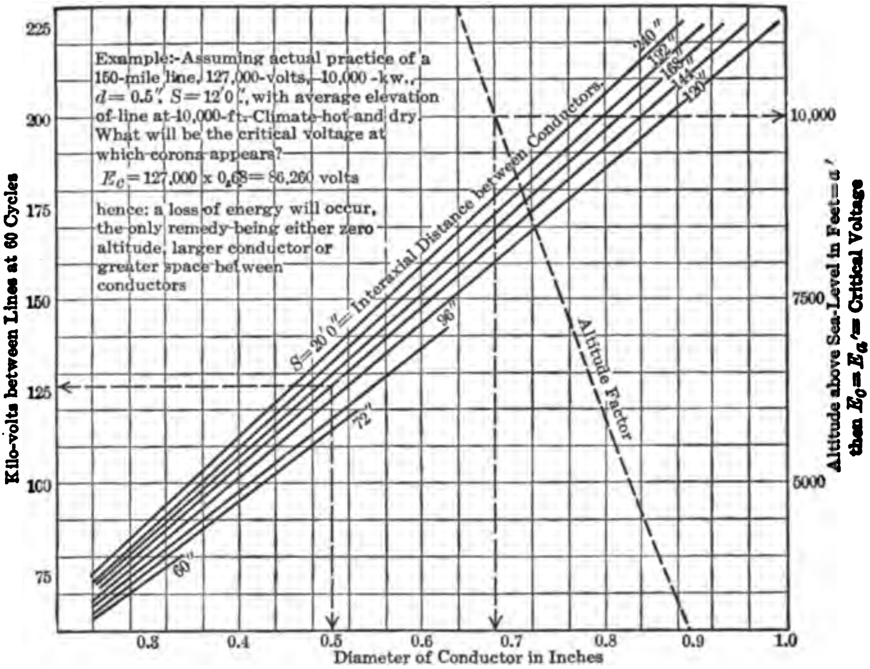

Fig. 156.—Curves Showing the Corona Limit of Voltage on Three-Phase Lines

In the above expressions,

C = capacity in farads.
E = Applied or line voltage for 3-phase system (Y voltage).
e = Effective applied emf. in kilovolts to neutral.
e_0 = Disruptive critical voltage in effective kilovolts to neutral.
f = Frequency in cycles per second.
k = Corona constant; is 344.
p_c = Corona loss in kilowatts per mile.
r = Radius of conductor in inches.
S = Distance between conductors in inches.
δ = Density factor; or $\frac{3.92\,b}{273 + t}$, where δ equals 1 at 25 deg. cent. and 76 cm. pressure.
b = Barometric pressure.
t = Temperature, deg. centigrade.

The corona loss is proportional to the frequency f, is proportional to the square-root of the conductor radius r and inversely proportional to the square-root of the conductor spacing S, and also proportional to the square of the excess voltage above the disruptive critical voltage, e_0.

Effect of Weather and Altitude on Line Operation.—The weather conditions that in practice must always be seriously considered in the design of transmission lines are numerous. Fog lowers the critical voltage and increases the loss. Sleet on the wires, or falling sleet, lowers the critical voltage and increases the losses. Rain storms lower the critical voltage and increase the loss. Snow storms have the greatest effect of any weather condition in lowering the critical voltage and increasing the loss. Barometric pressure must also be accounted for. Increased altitude has the effect of increasing the temperature rise or losses in not only a transmission line, but in many types of apparatus and machinery. It is now recognized that apparatus or machinery operating at altitudes above 3,000 ft. should be considered as special, and, when such is rated for service at altitudes above this value the normal permissible temperature rise should be reduced by about 1 per cent. for every 300 ft. by which the altitude exceeds the 3,000 ft. This also applies to all types of transformers excepting water-cooled.

Natural Line Impedance.—The magnetic energy stored in the line of self-induction L carrying current I is,

$$\frac{LI^2}{2}$$

When this current is suddenly interrupted the energy must change from the magnetic form to the static by charging the line as a condenser to a higher voltage E. The energy stored in the line having a capacity C at the added voltage E is,

$$\frac{CE^2}{2}$$

These two equations must be equal, so that $L\,I^2 = C\,E^2$

or $$E = I\sqrt{\frac{L}{C}}$$

commonly expressed as

$$E = Ik$$

where (k) is a constant and approximates 200.

The quantity $\sqrt{\frac{L}{C}}$ is of the nature of a resistance and is called the "natural impedance," equal to 138 log. $\frac{d}{r}$ ohms. It therefore lies between 500 and 200 ohms, the lower figure being chosen as shown above.

A rise of voltage always takes place across the reactance. If r^2 is equal to $\frac{4L}{C}$ the discharge takes place without oscillations, but just bordering on that condition. If the condition r^2 is less than $\frac{4\,L}{C}$ the charge oscillates until the energy is discharged in the resistance. Where r^2 is greater than $\frac{4L}{C}$ no oscillation takes place and no abnormal voltage is produced in the transmission line.

If E be the effective value of the voltage between lines, the maximum energy stored in the dielectric will be in the case of a delta-connected system (delta-delta) $\frac{E^2 C}{6}$, as compared with $\frac{E^2 C}{9}$ in the case of a star-connected system (delta-star) star on the high voltage side, the value (C) being the total capacity of the high-voltage transformer winding of each transformer to earth.

In general, resonance on account of the electrostatic capacity of the transmission line with a grounded star system is very unlikely, since the line capacity is not in series with the ground. This is not the case with the delta-connection which is in series with the electrostatic capacity of the transmission line.

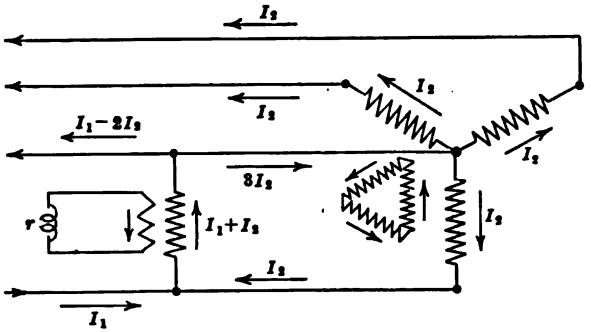

Fig. 157.—Current Relations in a Four Wire, Three-Phase System

Shifting of Static Neutral.—In a delta system the first phase closed will increase the capacity to ground of that phase of the system and thereby draw the static neutral toward the phase. The second phase acts in a similar manner and the static neutral does not return to the center of the delta until the three phases are closed. This sudden shifting of the static neutral is the cause of an unnecessary strain on the insulation of the system. Many failures of apparatus are recorded due to this cause. Not so with the star-connected system as a transmission line of any length may be charged at full voltage without shifting the position of the static neutral.

In four-wire three-phase systems, where the emf. is stepped up through delta-star transformers, and three-phase power is supplied through star-delta step-down transformers, the latter system of connections, if their neutral be connected to the neutral wire, serve as balancers for loads taken off between neutral wires and lines, as indicated in the accompanying diagram Fig. 157.

If the neutral point of the primary of the step-up star-star transformers be connected to the neutral point of the generators, the secondary neutral point on the star-connected high-voltage side will be stable. The loads may be supplied between the neutral point and the lines but, since the generators may have a third-harmonic component in the emf. between the neutral and terminals it is not advisable to ground the neutral point of the secondary windings. If, however, the high-voltage secondary windings be an interconnected-star, the neutral point may be grounded without causing the least trouble. The reason why the interconnected-star eliminates the third-harmonic is that there is an interchange of the third-harmonic mmf. due to the primary and secondary interactions of the interconnected transformer windings.

On account of their exposed position, transmission lines are the weakest link in the high-voltage transmission system. Even the failure of a single insulator may cause a complete shut-down of an entire system. It is therefore necessary that very careful consideration be given to the design and erection of such lines.* The right-of-way should be selected with a view to escaping land slides, floods, etc., and avoiding thickly settled districts when high voltages are to be transmitted. Where the lines pass through forests it is of greatest importance to have the right-of-way cleared on both sides of the lines wide enough so that there will be no possibility of falling trees or branches striking the lines.

Ground Wire Protection.—The value of ground wires for transmission lines cannot be judged by theory because their protection against lightning flashes is outside of the realm of calculation. On the other hand, their behavior in the case of sudden variations of the earth's field (lightning flashes in the neighborhood) can be calculated just like the charging currents of a transmission line. The ground wire diminishes the charge caused by the earth-field on the protected line. Further, it increases the capacity of the line against the earth. Since the voltage which the line assumes when the field breaks down is proportionate to the ratio of charge to capacity against earth, and since the charge is decreased and the capacity increased, the voltage produced on the transmission line is very much smaller than it would be if the line was not protected. These ground wires then, until something better is devised, are a valuable protection for overhead transmission lines.

The past few years' experience has shown that the overhead ground wire is of undoubted value for lightning protection and better results can be expected from two wires than from one. They should be placed as far above the transmission line conductors as possible and with a maximum shade angle of 45 deg. Their dimensions do not have any effect on protection

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* It is of interest to note that the horizontal arrangement of conductors as compared with the equilateral triangle arrangement of conductors gives a lower corona loss. This arrangement of conductors also gives a lower capacity current of the line. The lower corona loss and lower capacity result from the fact that the two outside conductors considered as a pair are twice as far apart as the other pair of conductors.

(protective action) so that they should be chosen from considerations of mechanical strength. When concrete foundations are used and the steel work does not extend through to moist earth it is necessary to make independent earth connections for a ground wire. These may consist simply of iron pipes driven into the ground and connected to the legs of the tower.

There is considerable difference of opinion among engineers as to the degree of protection secured by ground wires. It seems probable that this difference of opinion is largely due to the variability of lightning disturbances in different sections of the country. It is now generally agreed that modern high-tension lines, operating at 60,000 volts and over, are less subject to lightning disturbances than lower-voltage lines used to be. This, perhaps, is due to the better and more thorough insulation obtained with the modern disc suspension insulator. Well constructed tower lines are practically proof against indirect lightning strokes, although not against direct strokes of lightning which fortunately are of rare occurrence.

In selecting line insulators, a liberal factor of safety should be allowed, as they only form a small part of the total cost of the line and are the most vital factor in its satisfactory operation. Suspension insulators are now used exclusively for high-voltages above 60,000. The pin type of insulator is practically at its limit when operating at 60,000 volts. Numerous ingenious arrangements are used for connecting strings of suspension insulators in multiple to carry heavy stresses. For higher voltage transmission lines than at the present, the design of the suspension insulator must necessarily be modified so that the potential along the string can be better distributed. Further details of line construction and protection are given in the chapter IV devoted to this subject.

Oscillations from High-Voltage Switching.—High-voltage switching produces, in general, an abrupt change in the value of the emf. and of the current of the circuit, or of either, and therefore it produces a sudden change in the amount of energy stored in the circuit, with the result that oscillations are produced. The severity of these oscillations depends on the difference between the operating conditions before and after switching is done. If a dead line at zero potential is suddenly connected to the supply, the oscillation produced will be most severe when the switch makes the connection at the instant at which the emf. has its maximum value. If the dead line is suddenly connected to a live line having the same constants, a wave of charge, equal in value to one-half of the potential of the live line, starts along the dead line from the switching point. If the dead line is open from the far end, the wave of charge is reflected back at double potential. At the same time a wave of charge starts along the live line from the switching point with a value equal to one-half of the original voltage of the line. If the live line is connected at its origin to transformers, this wave of discharge is reflected back with double voltage and may excite local oscillations in the transformers or in the circuits of the power station. These traveling waves are a source of danger and the danger is increased when sparking and arcing occur at the switch.

To energize a line, it is preferable to connect the dead line to the step-up transformers and then, by low-tension switches, connect the line and transformer to the generators, rather than connect the transformers alone to the generators and then switch the line on the high-tension windings of the transformers. Wherever possible, it would be better still to connect the line and the step-up transformers and the generators together while the whole system is dead and then bring up the voltage to full potential by the excitation of the generators. This, however, is not possible during ordinary operation.

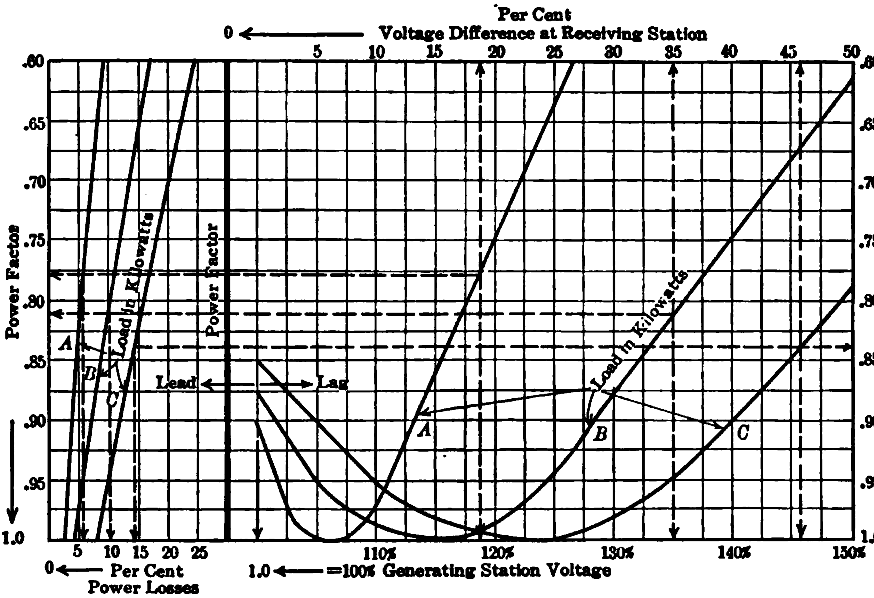

Fig. 158.—Curves for Typical Example of Generating and Receiving Station Voltages for High Voltage Long Distance Transmission with Different Loads and Power Factors

Line Charging Current.—In the transmission of electrical energy over long high voltage lines—voltages of 60,000 volts and over—the exciting or wattless currents produced are not only those for the inductive apparatus, but whatever is required by the transmission line itself. A transmission line has both inductance and capacity, both of which require exciting current. The leading current required by the capacity is of much greater magnitude than the lagging current required by the inductance, hence the exciting current to charge a transmission line is always leading, that is with reference to the generators. On some of the present day 110,000-volt lines, as much as 10,000 kva. is required to charge a single line under normal voltage conditions. For the 150,000-volt system of the Pacific Light and Power Company, 15,000 kva. synchronous condensers are used.

Line Voltage Regulation.—In the design of a transmission system, the voltage regulation must be within such limits on all parts of the system that satisfactory service is secured and, at the same time, all the transformers obtain proper exciting voltages and the lightning arresters be exposed to only safe dynamic voltages. Service for lighting loads is very exacting, since a 2 per cent. variation in voltage causes a change of approximately 8 per cent. in candle power. Service for power loads is not so exacting, nevertheless, it is of considerable importance, because on reduced voltage the starting torque and maximum horsepower of induction motors fall off as the square of the voltage. Since the power consumed by any load falls off as the square of the voltage, it is of great importance to power companies that the voltage be maintained as high as consistent with satisfactory service.

Transformers should have proper exciting voltage, because in general, a departure from normal rated voltage reduces the capacity for a given heating rise. By exciting voltage is meant the voltage applied on the side from whence the power comes. Reducing the voltage by a given per cent. reduces the kva. rating substantially by the same percentage, since the ampere capacity depends on the size of conductors. Increasing the voltage above normal decreases the output, because the exciting current is increased and also the core losses.

To prevent lightning arresters from being endangered by over-voltage, they should not be exposed to a voltage exceeding 15 to 20 per cent. Lightning arresters are designed to protect against transient voltages, and their characteristics are such that they offer protection only around their normal voltage rating. Should a lightning arrester be called upon to relieve a transient voltage, when the dynamic or steady voltage of the system is 15 to 20 per cent. above that at which the lightning arresters was charged, it would be exposed to serious damage, on account of the large flow of current occurring. Hence, it is not considered safe to expose lightning arresters to a voltage exceeding 15 to 20 per cent. above the normal voltage of the system. Further details of lightning arrester installation are given in the chapter devoted to line construction.

Use of Synchronous Condenser and Series Booster.—At a distribution center it is very desirable to have a flexible voltage, which can be increased as the load comes on, because with power feeders, the voltage drop due to the load may thus be compensated for within proper limits, and with lighting feeders, the feeder regulators are enabled to operate within limits of accurate regulation. A flexible generator and receiver voltage may be accomplished by means of a synchronous condenser and series booster, both machines arranged on the same shaft. The excitation of the synchronous condenser should be arranged for control with a voltage regulator and that of the booster by hand control. At the generating stations, the excitation should also be controlled by a voltage regulator. The function of the synchronous booster is to affect voltage compensation, the amount of buck or boost being controlled by the field excitation.

A desirable feature of synchronous condensers on a high voltage transmission system is that they offer protection against those voltage surges that arise due to a sudden loss of load which might throw the generating stations on the unloaded transmission line with their generators on heavy field excitation. Under such a circumstance due to the effect on the generators and transmission lines of the leading current, set up by the charging current, a destructive voltage will occur. Over-voltage devices may be applied to the generators to give protection, however, with synchronous condensers on the receiving ends of the transmission lines, and each one equipped with an over-voltage device, an ideal solution of the problem is effected.

CHAPTER VII

SPECIAL PLANT AND LINE PROBLEMS

I.—GENERATING AND SUBSTATION BUS STRUCTURES

Brick Compartments.—For station switch compartments, the question of concrete versus brick construction has been frequently discussed, and opinions as to which is preferable will always differ. However, at the present time the majority of engineers who are designing bus structures seem to favor brick. Other materials, such as hollow tile and hollow concrete brick with grout poured in later, have been and are now being tried out with varying results.* There are two strong arguments in favor of brick,—first, the possibility of making changes and installing new switches in an old structure; second, the good appearance of brick.

The general run of bricks used for bus structures measure 4 in. by 8¼ in. by 2¼ in. The walls will therefore be 4 in. or 8¼ in., and in some extreme cases 12½ in. thick, allowing ¼ in. for a joint. Through bolts with washers should be set in the 8¼ in. wall for holding oil switches and other heavy apparatus. However, it will often be found cheaper to drill the walls and use expansion bolts for apparatus of small weight, such as disconnecting switches, insulators, instrument transformers and the like. It is not advisable to drill 4 in. brick walls, as the thin wall will not usually withstand a heavy hammer. It may be considered good practice whenever it is possible to make the vertical spacing of bolts a multiple of 2½ in., so that the bolts can be set in a brick joint. Forged bolts can be used for such purposes and have been used in many cases with good results.

Installation of Bus-structure Equipment.—Insulators for supporting buses and other live parts should be as compact as possible, and should be bolted or clamped to the wall or slab. They should not be cemented into the wall or slab, since this construction causes considerable disturbance in operation when it becomes necessary to exchange an insulator. When clamping bus insulators, the clamp should be made in two parts to avoid the necessity of lifting the bus when exchanging an insulator. For bolting down insulator pins, slots can be conveniently provided in the insulator pin instead of bolt holes.

Oil-switch cell doors may be made either of asbestos wood or sheet iron, with angle or channel framing. It is advisable to suspend the door from

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* *Electrical World*, Jan. 15, 1916.—The Design of Power Station and Substation Bus Structures, by M. M. Samuels.

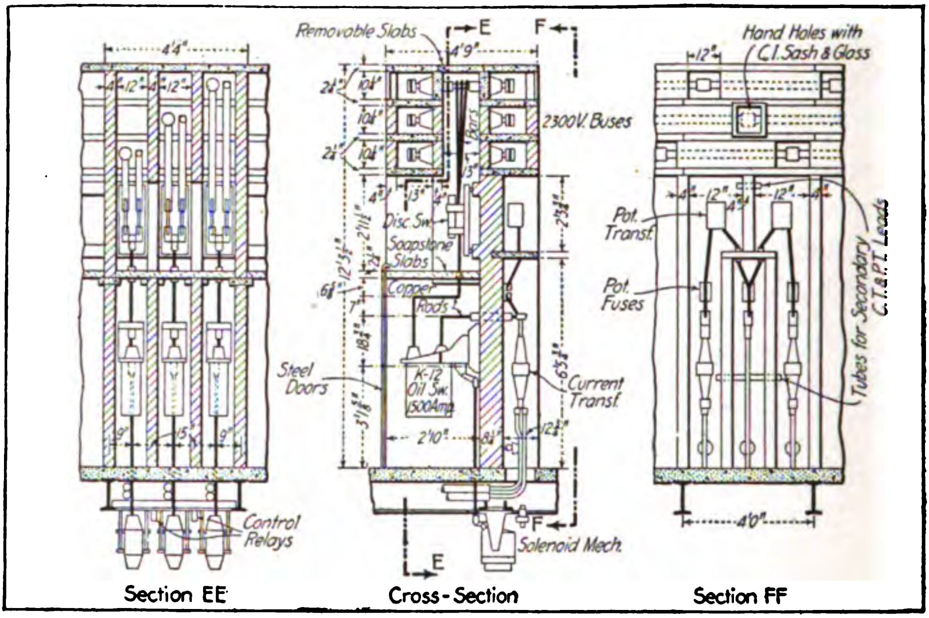


Fig. 159.—Double-Bus Structure in Station of Wilmington and Phila. Traction Co.

In this case 2300-volt 800 amp. and 1500 amp. General Electric type K-12 oil switches are used. The solenoid mechanism and operating relays are mounted on steel work under the floor. By means of disconnecting switches the oil switches can be thrown to either bus. The structure is of brick.

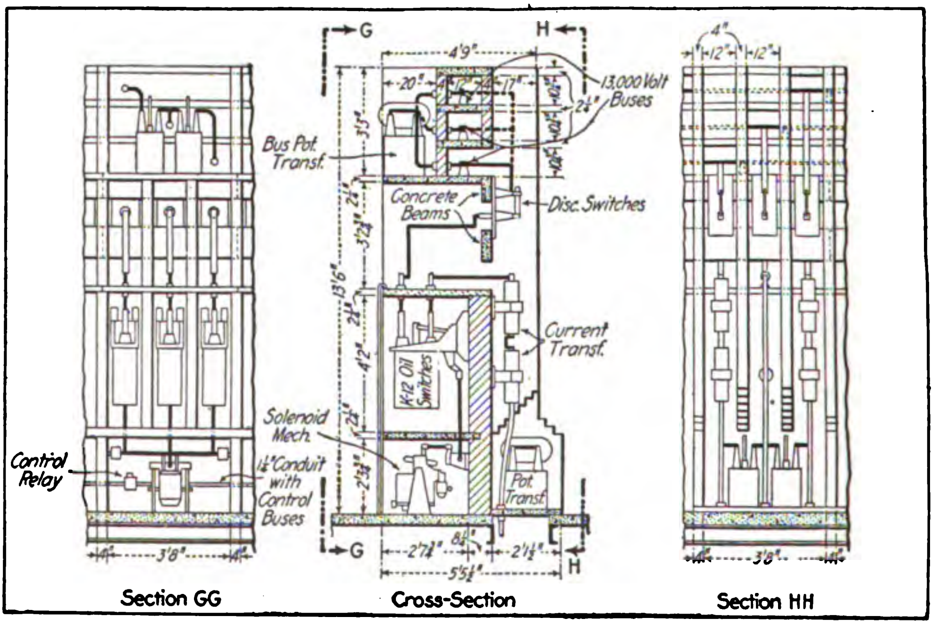


Fig. 160.—Structure in Augusta (Ga.) Substation of Georgia-Carolina Power Co.

In this case 13,000 volt, 300 amp. and 500 amp. General Electric type K-12 oil switches are used. Between the oil switches and buses are disconnecting switches back-connected at one end. The solenoid mechanism is placed in a compartment under the oil switch. The structure is of brick.

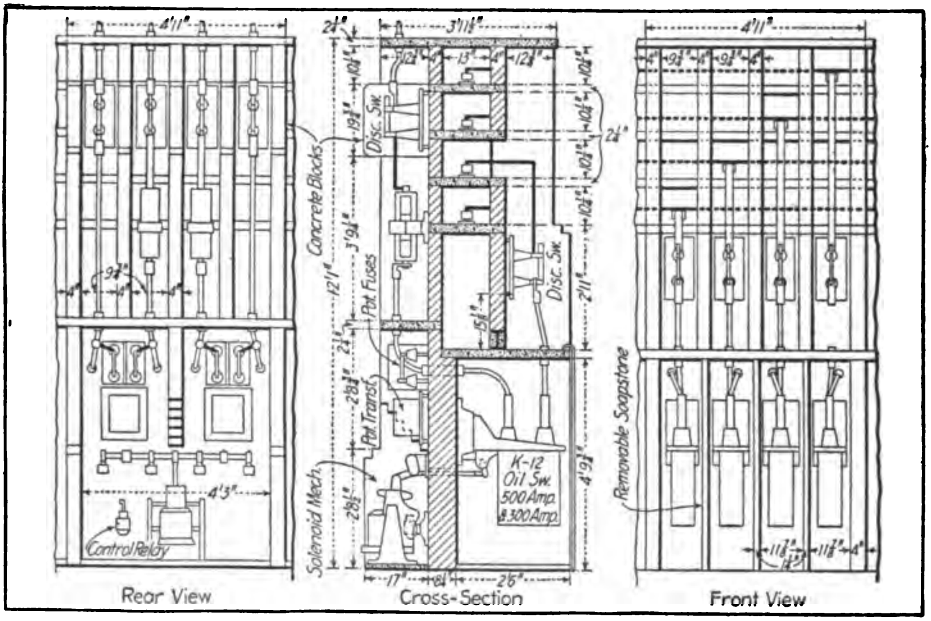


Fig. 161.—Brick Bus Structure in Substation of Tri-City Railway and Light Co.

Here 4800 volt two-phase, 300 amp. and 500 amp. General Electric type K-12 switches are used. Disconnecting switches are installed on both sides of the oil switches. The solenoid mechanism is placed on the floor in the rear of the oil-switch cell. Removable soapstone barriers separate the poles.

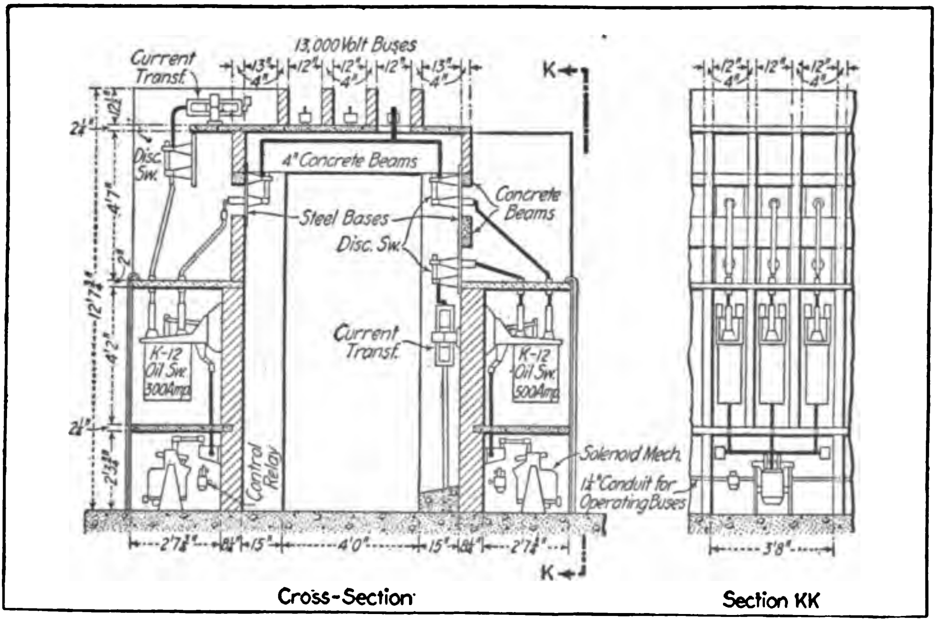


Fig. 162.—Double-Row Structure in Columbia (S. C.) Substation of Parr Shoals Power Co.

In this case 13,000 volt, 300 amp. and 500 amp. General Electric type K-12 oil switches are used. A 4-ft. passageway runs between two rows of cells. Common buses are installed over the passageway. The slabs under the buses are on concrete beams which serve as barriers between phases.

TABLE 47.—DATA ON SEVERAL BUS STRUCTURE INSTALLATIONS

Fig. No.	Voltage	No. of Phases	Type of Oil Switch	Location of Mechanism	Width of Cell	Length of Cell	Height of Structure
159	2,300	Three	G. E. type K12	Under floor	4 ft. 9 in.	4 ft. 10 in.	12 ft. 3½ in.
160	13,000	Three	G. E. type K12	On floor under oil switch	5 ft. 5½ in.	4 ft. 0 in.	13 ft. 6 in.
161	4,800	Four	G. E. type K12	On floor in rear of oil switch	4 ft. 7½ in.	4 ft. 7 in.	12 ft. 1 in.
162	13,000	Three	G. E. type K12	On floor under oil switch	10 ft. 8 in. for two cells and passageway	4 ft. 0 in.	12 ft. 7¾ in.
163	6,600	Three	G. E. type H3	On top of cell	5 ft. 6 in.	4 ft. 6 in.	11 ft. 1 in.
164, 165, 166	2,300	Three	West. type E—1200 amp.	On top of cell	7 ft. 9 in. for two cells and passageway	4 ft. 3½ in.	10 ft. 10½ in.
164, 165, 166	2,300	Three	West. types E and C—2000 amp.	On top of cell	8 ft. 1 in. for two cells and passageway	5 ft. 3¾ in.	10 ft. 10½ in.
167	13,000	Three	G. E. type H3	On top of cell	5 ft. 6 in.	4 ft. 6 in.	. .

the top without bolts at the bottom so that it can swing out automatically in case of air pressure inside the cell caused by an oil-switch blow-out. In some cases where the cell doors have been bolted considerable damage has been done to structures and apparatus from oil-switch explosions.

Special attention should be paid to the layout of potential transformers, especially when

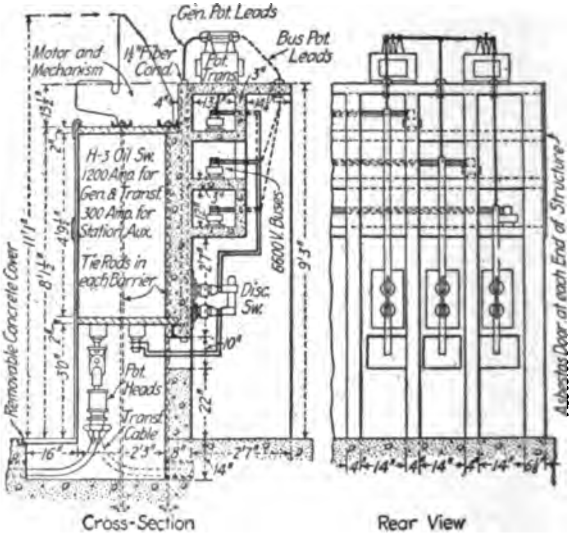


Fig. 163.—Concrete Structure in Ocoee (Tenn.) Power Station No. 2 of Tennessee Power Company

In this installation 6600-volt, 1200-amp. General Electric H3 oil switches are used. Reasons for concrete: (1) Large number of conduits had to be run through main wall; (2) owing to lack of space barriers between poles inside oil switch, cell could not be made more than 3 in. thick. Compartment under oil switch accommodates potheads for 1,500,000-circ. mil cables. A pit is provided for cable pulling.

the voltage is above 2300. Potential transformers and potential fuses for higher voltages require considerable space and have to be installed in certain positions, especially oil-cooled transformers and expulsion-type fuses, so that if in the preliminary design these points are not taken into consideration considerable difficulty may be encountered in finding suitable accommodation for them.

In most cases it will be possible to install a positive and negative operating bus at the bus structure, and the control cables from the switchboard to each oil switch may be made up of three conductors, which can be installed in a ¾ in. conduit instead of the five-conductor cables which would be required when no buses are provided at the structure and which need 1¼ in. conduits. The operating buses should be installed in conduits, with outlet boxes at each oil switch. In the structure shown in Figs. 160 and

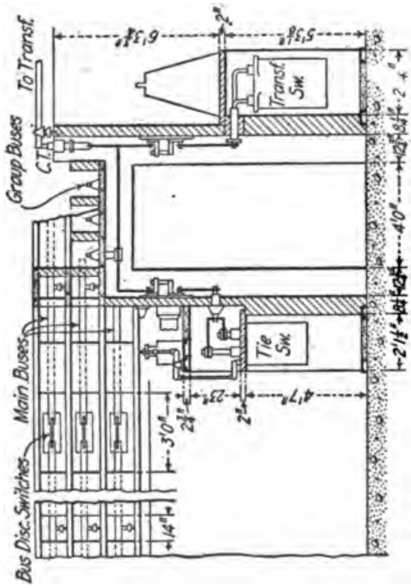


Fig. 165

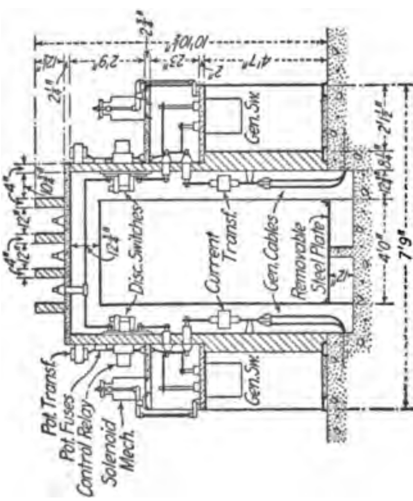


Fig. 164

Figs. 164 and 165.—Arrangement of Equipment in a Brick Structure in Power Station of Parr Shoals Power Company. (See also Fig. 166)

The structure consists of several blocks of switching and a continuous bus structure which is 205 ft. long. Each block contains two generator switches (1200-amp. non-automatic Westinghouse type E), one transformer switch (200-amp. automatic Westinghouse type C), and one tie switch (2000-amp. non-automatic Westinghouse type E). One generator and tie switch are installed on one side and the other generator and transformer switches on the other side of passageway.

162 the control buses are installed in one 1¼ in. conduit, which is used at the same time for mounting the operating relays.

When current and potential transformers are installed in separate compartments, holes should be left in the partition walls to accommodate conduits for the secondaries between phases, and in case of potential transformers porcelain tubes should be provided for the primaries. Fiber conduit is being satisfactorily substituted in some cases for porcelain tubes.

The shape and general design of bus structures will generally depend on the following conditions: (1) Type of oil switches, current transformers, potential transformers and disconnecting switches; (2) whether disconnecting switches are installed on one side or both sides of the oil switch; (3) on the amount and direction of the available space—that is, the structure may be made wide, long or high; (4) whether the cables leave the structure overhead or underground; (5) arrangement of solenoid or motor mechanism. It cannot be impressed too strongly upon the manufacturers of new oil switches to build the solenoid or motor mechanisms so that they can be placed in many different locations in relation to the oil switch. The influence of the flexibility of oil-switch mechanism on bus-structure design can be clearly seen in Figs. 159, 160, 161 and 162.

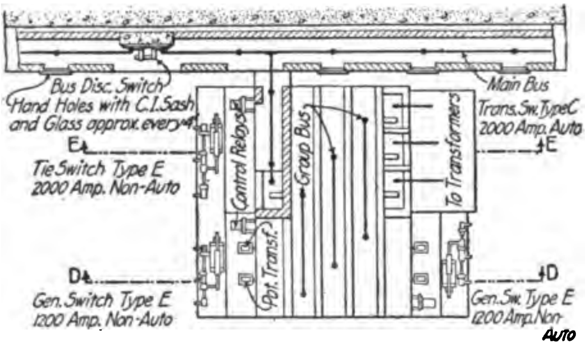
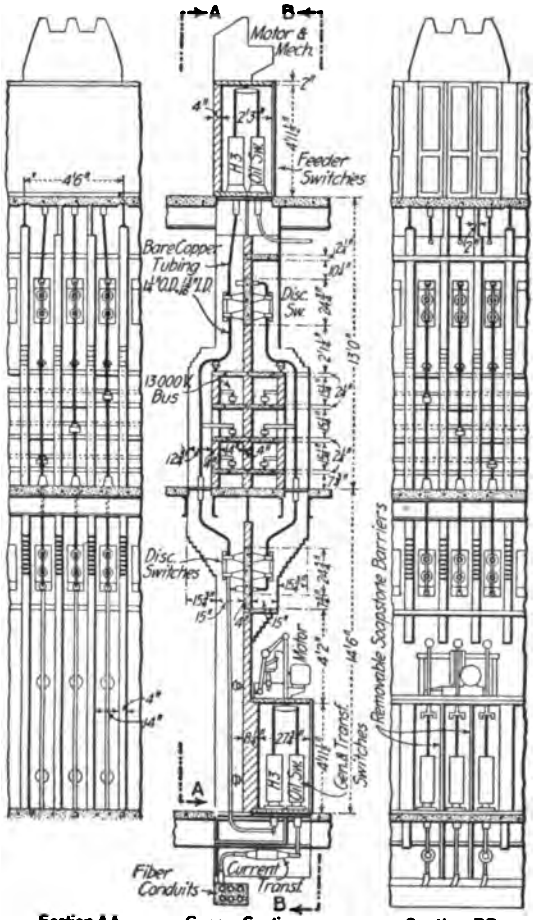

Bus Disc. Switch
Hand Holes with C.I.Sash and Glass approx. every 4'
E
Tie Switch Type E 2000 Amp. Non-Auto
D
Gen. Switch Type E 1200 Amp. Non-Auto
Control Relays
Pot. Transf.
Group Bus
To Transformers
Main Bus
Trans. Sw. Type C 2000 Amp. Auto
E
D
Gen. Sw. Type E 1200 Amp. Non-Auto

Fig. 166.—Main and Group Bus Arrangement in Structures at Power Station of Parr Shoals (S. C.) Power Company

II.—OUTDOOR SUBSTATION DESIGN

Outdoor Station Requirements.—An electrical structure, to be strong electrically and mechanically, should have the least number of insulating supports practicable. This principle has been observed especially in connection with high-tension transmission lines as evidenced by the use of strain-type insulators instead of pin or post-type units. This practice permits employing fewer poles and insulating supports, thereby simplifying the construction and reducing the cost thereof, at the same time minimizing sources of trouble. Too generous use of strain insulators in station construction, however, should be guarded against, since opposite effects are generally produced. Strain insulators are not intended for short spans, since they occupy a relatively large amount of space and leave only a small portion of the span in which to make connections, thus requiring excessive offsets in wires. When used for station wiring they require a large number of crossings, loops and indirect runs, possibly crowding the conductors into several horizontal or vertical planes and sometimes making them inaccessible unless the entire station equipment is de-energized. For lightning arrester connections, especially, it is inadvisable to use strain insulators, chiefly because of the loops and extra insulators necessitated and the higher poles required to secure the proper ground clearance. Because of the objections mentioned it is suggested that rigid busbars and connections be employed in outdoor stations, thus making it possible to reduce the number of insulating supports and eliminate the use of strain insulators. For busbars, copper pipes or bars are preferable.



Section AA Cross-Section Section BB

Fig. 167.—Double-Bus Three-Story Brick Structure in Terminal Station of Canadian Light & Power Company

In this case 13,000-volt General Electric H3 oil switches are used. Each oil switch can be connected to each bus by disconnecting switches. Two disconnecting switches and tie bus are mounted on common 4-in. concrete blocks set in the brick wall. Buses are made of bars. Connections are of 1¼-in. outside-diameter copper tubing. Removable soapstone barriers are used as in Fig. 161.

Example of Good Construction.—The features of design mentioned were observed in the layout and construction of the Pennsylvania Utilities Company's outdoor substation at Dock Street, Easton, Pa., as described by M. M. Samuels in the *Electrical World* for April 15, 1916, and the accompanying illustrations show how the details of construction were worked out. The substation is situated alongside the company's steam generating station, the control switchboard being located inside the latter and next to the generator switchboard. Provision has been made for ultimately installing four banks of three 1000-kw., 33,000/2300-volt, single-phase transformers and an equal number of 1000-kw., 11,000/2300-volt units with the necessary auxiliary apparatus.

EQUIPMENT IN OUT-DOOR SUBSTATION AT EASTON, PA.

Transformers: Two banks of three single-phase, 500-kw., 33,000/2300-volt transformers and one bank of three single-phase, 750-kw., 11,000/2300-volt units. Three 1000-kva., 11,000/2400-volt and four 1500-kva., 33,000/2400-volt transformers have been ordered.

Switches: Two banks of three K-22, single-phase, 33,000-volt, waterproof transformer oil switches and three banks of similar type line switches. One bank of three K-12, single-phase, 11,000-volt transformer switches and six banks of similar line switches.

Lightning Arresters: Three 33,000-volt and six 11,000-volt four-tank electrolytic cells. This apparatus was furnished by the General Electric Company.

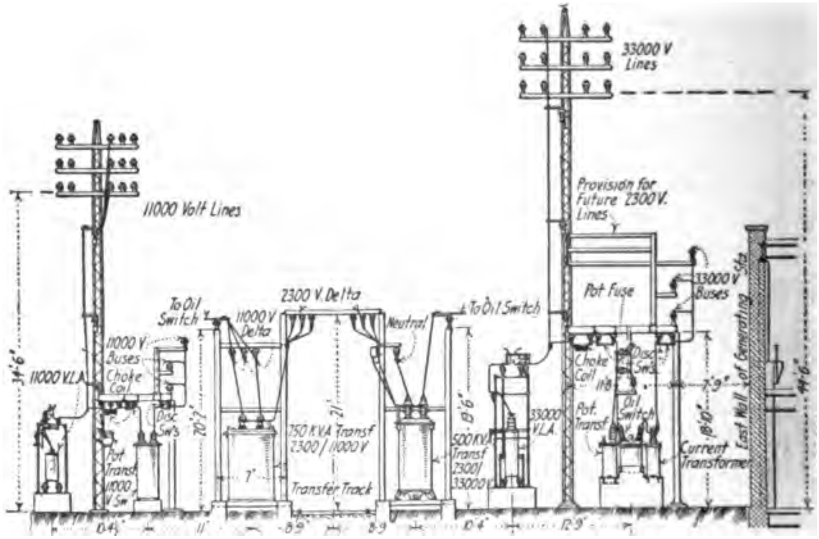


Fig. 168.—Cross-Section of Outdoor Substation Showing 33,000 Volt and 11,000 Volt Outgoing Lines and Arrangement of Busbars on Steel Superstructure

This apparatus is connected with four 33,000-volt and seven 11,000-volt, three-phase circuits, there being in addition several 2300-volt circuits radiating from the generating station and passing through the outdoor substation. As indicated in the accompanying drawings, the 33,000-volt equipment is arranged in three parallel rows on the side nearest the generating station, while the 11,000-volt apparatus is similarly laid out along the far side. Tracks are provided between the two groups so that the transformers, which are mounted on wheel trucks, may be moved into the station for repair or inspection purposes. Each bank of K-22 switches is operated by a single solenoid mechanism mounted on one side of the switch foundation and enclosed by a waterproof case which also houses the operating relay. The 33,000-volt current and voltage transformers are of the outdoor types and are mounted on the foundations of their respective switches. The K-12 switches are not waterproof, so they are inclosed in a sheet-steel housing which also accommodates the 11,000-volt current transformers and switch-operating mechanisms.

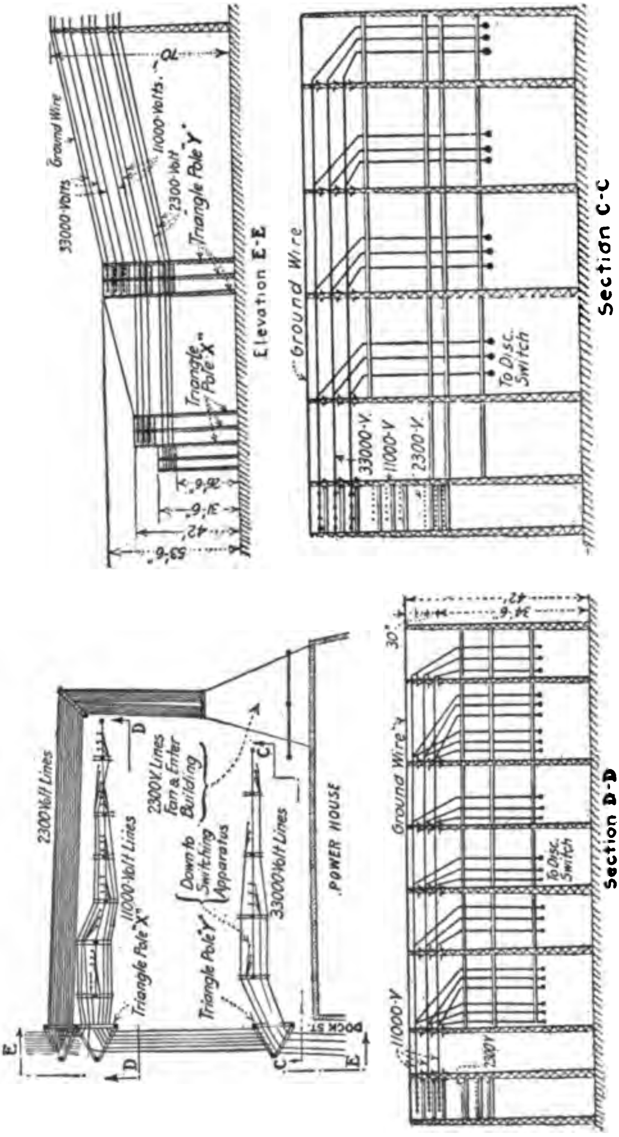


Fig. 169.—Outgoing Lines on Substation Superstructure; Lines Leaving Outdoor Structure (E-E); and Methods of Connecting 11,000 Volt and 33,000 Volt Lines with Equipment, Overhead Circuits being in Vertical Planes

Except for the 2300-volt transformer leads and control circuits all of the conductors are carried overhead by a steel structure made up chiefly

TABLE 48.—DIMENSIONS AND RATING OF TUBING WITH CONTACT LENGTHS FOR CLAMP JOINTS

NOMINAL SIZE OF PIPE, INCHES	OUTSIDE DIAMETER, INCHES	OUTSIDE CIRCUMFERENCE, INCHES	STANDARD IRON PIPE SIZE						EXTRA HEAVY IRON PIPE SIZE					
					Copper		Brass or Aluminum				Copper		Brass or Aluminum	
			Inside Diameter, Inches	Sectional Area of Metal, Square Inches	Maximum Carrying Capacity, Amperes	Minimum Length of Contact, Inches	Maximum Carrying Capacity, Amperes	Minimum Length of Contact, Inches	Inside Diameter, Inches	Sectional Area of Metal, Square Inches	Maximum Carrying Capacity, Amperes	Minimum Length of Contact, Inches	Maximum Carrying Capacity, Amperes	Minimum Length of Contact, Inches
1/8	0.405	1.27	0.281	0.066	66	3/8	43	3/8	0.205	0.095	95	1/2	62	9/16
1/4	0.540	1.70	0.375	0.117	117	1/2	76	1/2	0.294	0.161	161	11/16	105	11/16
3/8	0.675	2.13	0.494	0.163	163	9/16	106	9/16	0.421	0.218	218	11/16	142	3/4
1/2	0.840	2.64	0.625	0.246	246	5/8	160	11/16	0.542	0.323	323	13/16	210	7/8
3/4	1.050	3.30	0.822	0.335	335	11/16	218	3/4	0.736	0.440	440	15/16	286	15/16
1	1.315	4.12	1.062	0.470	470	3/4	305	13/16	0.951	0.648	648	1 1/16	420	1 1/8
1 1/4	1.660	5.21	1.368	0.694	694	7/8	450	15/16	1.272	0.893	893	1 3/16	582	1 3/16
1 1/2	1.900	5.98	1.600	0.824	824	15/16	538	1	1.494	1.082	1082	1 1/4	710	1 1/4
2	2.375	7.45	2.062	1.087	1087	1	710	1	1.933	1.495	1495	1 3/8	975	1 7/16
2 1/2	2.875	9.01	2.500	1.583	1583	1 3/16	1020	1 3/16	2.315	2.282	2282	1 11/16	1480	1 3/4
3	3.500	11.00	3.062	2.257	2257	1 3/8	1480	1 7/16	2.892	3.052	3052	1 7/8	2000	1 15/16
3 1/2	4.000	12.60	3.500	2.945	2945	1 9/16	1920	1 5/8	3.358	3.710	3710	2	2410	2
4	4.500	14.20	4.000	3.338	3338	1 5/8	2170	1 5/8	3.818	4.455	4455	2 1/8	2900	2 3/16
4 1/2	5.000	15.70	4.500	3.730	3730	1 5/8	2430	1 11/16	4.250	5.450	5450	2 5/16	3510	2 3/8
5	5.563	17.47	5.062	4.180	4180	1 5/8	2710	1 11/16	4.813	6.113	6113	2 3/8	4000	2 7/16
6	6.625	20.81	6.125	5.006	5006	1 5/8	3270	1 11/16	5.750	8.496	8496	2 3/4	5500	2 3/4

Lengths of contact given in above table refer to clamp joint.

of latticed steel columns, angle irons and channels. Between the power house and the outdoor 2300-volt busbars the circuits are run through fiber conduit embedded in concrete. The 2300-volt busbars consist of 2 in. by ¼ in. copper bars suspended from steelwork over the transfer track by pin-type insulators. The 33,000-volt and 11,000-volt busbars are arranged in vertical planes over their respective switches to permit fanning out and connecting with proper equipment.

The 11,000-volt connections and the 33,000-volt busbars and connections consist of 0.5 in. copper tube, but the 11,000-volt busbars are made of 1 in. copper tube (iron-pipe sizes). Standard pin-type insulators with General Electric caps are employed to support the busbars, the latter being attached to the caps by 1 in. by ⅛ in. brass straps. The insulators are mounted on angle-iron cross-arms connected with the general steel framework. Tee connectors were employed to splice branch circuits to the copper tubing, a clamp joint being used on the bus and a slip-and-shrink joint on the branch circuit. Table 48 gives data for copper tubing and lengths of contact required.

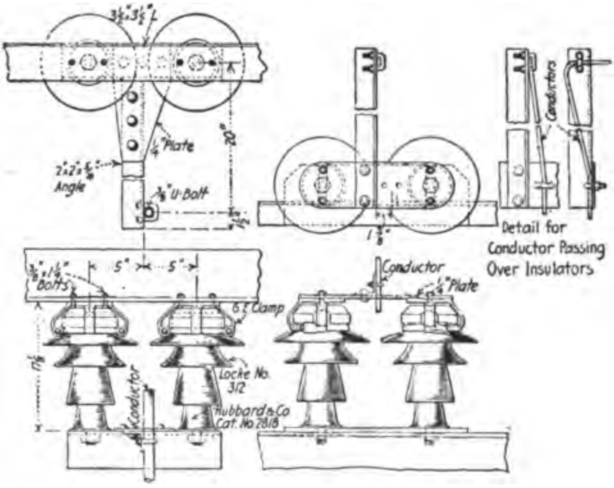


Fig. 170.—Insulated-Bracket Support for Vertical Conductors that Permits Installing Pin Type Insulators in Natural Position

The lightning arrester horn gaps are mounted on pipe framework over their respective tanks. All choke coils and disconnecting switches are suspended from steel bases, being attached thereto by pin-type petticoat insulators. Potential fuses are disconnecting switch type.

In no case were pin-type insulators inclined from the vertical to support vertical or sloping runs of conductors. Instead, special supports were constructed by tying together with steel plates two pin-type insulators as shown in Fig. 170. At right angles to one of the plates connecting the insulators was fastened an angle iron. A U-clamp in one end of the bracket thus formed and another in the tie plate hold the conductor at the proper distance from the pole and cross-beam and permit making right-angle bends in the conductor without depreciating the function of the insulator. The insulators supporting vertical runs are similar but have U-clamps only at the end of the angle-iron bracket.

The 11,000-volt lines lead from their respective switches to a triangle-section pole, indicated as *X* in Fig. 169 (E-E), and from there extend in the direction of the transfer track to another triangle-section pole, *Y*, opposite the 33,000-volt switches. From this point on the 33,000-volt and 11,000-volt circuits, as well as some 2300-volt feeders, are carried on jointly-used poles.

Clearances for Live Elements.—All of the outdoor substation apparatus is mounted so that no "live" parts are within reach of persons standing on the ground. Furthermore, such clearances were used between "live" parts and ground that little possibility of interruptions to service by flash-over will be afforded. In the absence of recommendations by any authoritative body on standard clearances the values given in an accompanying table were considered conservative.

Table 49.—Clearances Used in Easton [Pa.] Substation Design

Voltage Not Exceeding	Clearance Between Live Parts, in Inches		Clearance of Live Parts to Ground, in Inches	
	Minimum	Recommended	Minimum	Recommended
7,500	12	15	4	6
15,000	18	21	6	8
27,000	27	30	8	10
35,000	33	36	11	14
47,000	42	46	14	17
70,000	60	66	21	26
88,000	72	80	27	34
100,000	80	90	30	38
140,000	100	120	42	50

III.—High Tension Fuse and Switch Operation

Requirements of Fuses in Small Substations.—Reliable and uninterrupted service from the modern high-tension transmission system largely depends upon the methods of relaying the switching so that the line or piece of apparatus in trouble will be automatically dropped in as short a time as possible. With the proper adjustment of such a method it has been found that in the majority of cases the trouble will clear itself and that the line can be replaced in service immediately. The cost of repairs on all lines is also greatly reduced with such operation. Oil switches and relays have now been developed to such a stage that this scheme can be carried out in installations that will warrant the expenditure. There are many cases, however, where it is desirable to serve customers whose business is too small to warrant the installation of anything but the simplest apparatus and control. Protection against overload and apparatus failure is in these cases essential and general practice is now calling for the installation of a high tension fuse of suitable design and characteristics.

High Tension Fuse Characteristics.—To be acceptable for modern high-tension operation, a fuse should embody the following characteristics.* It should break the circuit in which it is installed under short-circuit conditions in a short period of time, say in thirty or forty cycles at the longest. It must be made of a metal that has a definite time-current characteristic that is unaltered by successive heating and cooling or by age. It must be constructed so that it will positively prevent arcs blowing or forming from phase to phase.

While there may be other metals that are equally good for use in fuse construction, annealed copper wire is largely used in all high-tension work. The principal reasons for the use of this wire are that copper is more readily obtained in desired sizes, and data covering its electrical characteristics are more complete.

It is not a difficult matter to compute the time-current characteristic curve of a copper-wire fuse of given size, as all of the factors that cause the fusion of the copper are perfectly definite and can be calculated by well-known laws of physics. The heat required to fuse a wire is the sum of the heat necessary to raise the temperature of the wire from air temperature to the temperature of fusion for copper, plus the latent heat of copper, plus the heat lost in radiation. The heat lost in radiation is relatively small, ranging from 5 per cent. to 10 per cent. of the total heat, and can be neglected without seriously affecting the results. Also, the heat generated in a given size of wire by a given current is simply the product of the I^2R loss in watts in the wire by the time in seconds by a conversion constant of 0.0009478. The result is in (F. P. S.) units of heat. Knowing the heat required to fuse a unit length of wire and the heat generated per second in any size of wire by a given current, the time that is required to fuse the wire by different values of current may be computed. It is a good plan to plot a set of curves between time and current for all sizes of wire from No. 10 B. & S. to No. 30 B. & S. for reference use. Such a curve for No. 18 wire is shown in Fig. 172.

Selecting Size of Copper Wire Fuse.—From impedance calculations of transmission lines and generators it is possible to compute what value of short-circuit currents to expect at different points. Knowing this, a size of fuse may be installed that will give the selective action desired at any point. For example, consider the following case, illustrated in Fig. 171, Suppose a feeder leaves a substation through an automatic oil switch *A*, equipped with definite time-limit relays, and connects with station *F*, serving on the way stations at *B* and *D*. *C* and *E* are fused sectionalizing switches at substations *B* and *D* respectively. Let us say that from line calculations 300 amp. will flow into a short-circuit at *F*, 400 amp. at *D*, and 500 amp. at *B*. The oil switch should be considered as a reserve and set so as to trip on a short-circuit, even at the very end of the line, so as to guard against fuse failures. It must have a time setting long enough to give the fuses time to operate. In this case a setting of 275 amp. and 3 seconds would probably be satisfactory. Trouble at *F* should be cleared off without disturbing service to substation *B* or *D*. This may be accomplished by installing a fuse of No. 20 B. & S. wire at the fused switch *E*, which will fuse in 1.2 seconds with 300 amp. flowing through it, thus beating the relay setting of 3 seconds at *A*. Likewise a No. 18 B. & S. wire installed at *C* will open in 1.7 seconds when trouble develops at *D* and in advance of oil switch *A*. With a "short" at *F* of 300 amp. this fuse will open in 3.2 seconds, which is a longer time than required by the fuse at *E*. Trouble between *A* and *C* must then be taken care of by the operation of the oil switch *A*.

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* *Electrical World*, Dec. 11, 1915, page 1305.—The Design and Operation of Horn Gap Fuses, by E. A. Dillard, Alabama Power Company.

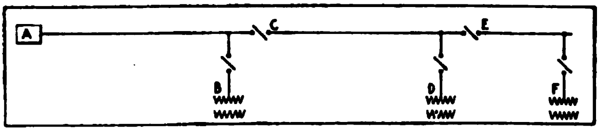

Fig. 171.—Substation Layout Showing Desirability of Selective Action of Fuses

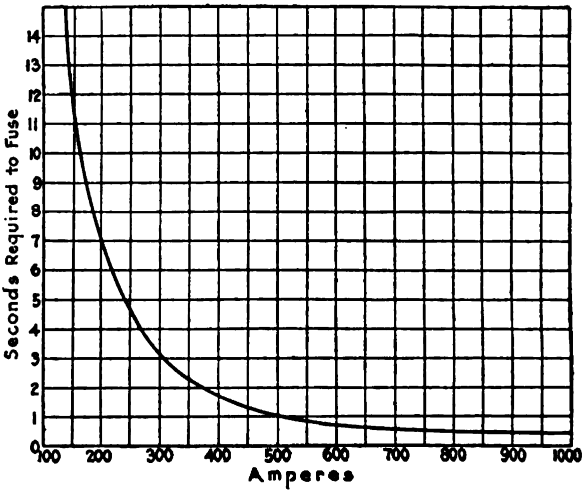

Fig. 172.—Time-Current Characteristic for No. 18 B. & S. Gage Annealed Copper Fuse Wire

Faults of Open-type Horn Gap Fuses.—When open-type horn-gap fuses are installed considerable trouble is often experienced in making the fuses operate in a definite manner. The difficulty is not in determining the time required to melt the copper but in making a reliable estimate of the time required to clear off the arc that results from the fuse opening. Even with horns properly shaped to break an arc in the fastest time, it is found that with the fastest horns the time required to break an arc is comparatively a long period and varies with the amount of current in the arc. Besides this, the horn type fuse presents an additional difficulty, as the arcs resulting from a set of fuses opening are liable to intermingle giving a second short-circuit which is dangerous, when they are near the source of power.

Numerous improvements have been proposed for use in fuse horns to take the place of open fuses. One of the most satisfactory has been the fuse made up of fiber tubes packed with plaster of paris. These designs usually break an arc in a short time, but are mechanically weak. The tubes are liable to burst and give an arc as serious as the open type fuse. Another type of fuse that has been used consists of a glass tube (gage glass) packed with plaster of paris and stoppered at each end. The glass breaks and most of the time extinguishes the arc, but there is a chance of failure that would also give a bad arc.

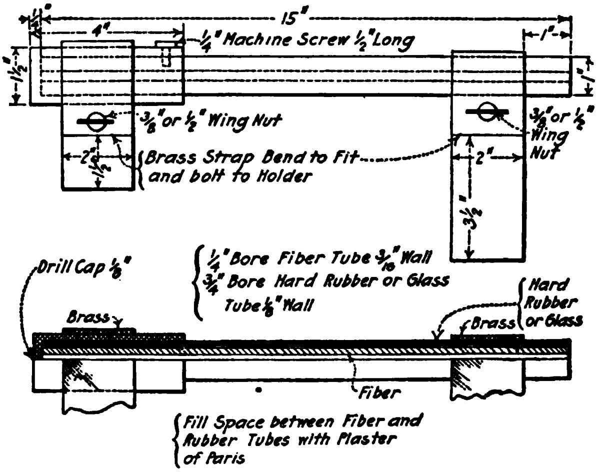
15"
1/4"
4"
1/4" Machine Screw 1/2" Long
1"
1 1/2"
1"
3/8" or 1/2" Wing Nut
3/8" or 1/2" Wing Nut
Brass Strap Bend to Fit and bolt to Holder
2"
1 1/2"
2"
3 1/2"
Drill Cap 1/8"
1/4" Bore Fiber Tube 3/16" Wall
3/4" Bore Hard Rubber or Glass Tube 1/8" Wall
Hard Rubber or Glass
Brass
Brass
Fiber
Fill Space between Fiber and Rubber Tubes with Plaster of Paris

Fig. 173.—A Combination Glass and Fiber-Tube Type of Fuse Arranged to Fit 100-Amp. 600-Volt Knife-Switch Clips

Expulsion Types of Fuses.—There are a number of fuses on the market that are satisfactory for high tension work. In Fig. 173, a home-made fuse devised by E. A. Dillard of the Alabama Power Company is shown which has given good service, is accurate and may be replaced at a small expense. This fuse is made of a fiber tube sealed in a glass tube and capped at the end by a heavy brass fitting. Fiber itself is hard to waterproof satisfactorily, so that the entire tube has been inclosed in glass. The ends of the tube are sealed with a cement to prevent moisture from entering. The contacts are made of strap brass of such a size as to fit into 100-amp., 600-volt knife-switch clips. The front contact strap is made longer than the rear strap, so as to elevate the mouth of the fuse. This throws the arc out and away from the supporting insulators. Mounted in this way, there is also considerable force placed on the fuse, tending to throw it out of the holder. As the arc clears off practically instantaneously, there is no danger of the switch clips having to break any part of the arc. It is important to double the fuse wire to a point about one-half way in the tube. This insures the fusion inside the tube and near the rear end.

These fuses have been found nearly as satisfactory in their operation as an automatic oil switch, excepting that it is possible to obtain only one automatic feature, namely, inverse time limit. Of course, with oil switches there are many combinations that can be worked out by using definite time-limit relays and reverse-energy relays, but in the protection of a straight power feeder these features are not often required. Further, an automatic oil switch for 22,000-volt service costs at least $600. A set of horn-gap fuses installed costs less than $50, and may be refilled at a very small cost. While there are many features favoring use of an oil switch, every operating engineer appreciates that there are many cases in which a profitable business can not be secured unless an inexpensive substation can be installed and satisfactorily operated. In these cases the question of protection can often be met by the installation of an air-break switch fused with expulsion-type fuses.

Rating of Oil Switches.—When oil switches or circuit breakers are rated on the amount of synchronous apparatus or generating equipment connected to a system, such a rating is limited to the reactance and short-circuit characteristics of the apparatus and to the particular circumstances under which it is installed and operated. Unless the oil switch is installed at the generator, the machine impedance which is variable during the first few seconds of short circuit must be added vectorially to the impedance of the lines, transformers and other apparatus up to the point of short circuit when calculating the size of oil switch required. A unit suitable for a power station then will be too large for a line substation. There is considerable difference of opinion on the basis for rating oil switches and there is little agreement on the maximum operating limits of a unit of a given rating. What seems to be a logical method is advocated by the Westinghouse Electrical & Manufacturing Company and described by J. B. McNeill in the August, 1916, issue of the *Electric Journal*, as based on the ultimate or actual arc kva. This is equivalent to the product of current during the first cycle after the switch contacts commence to open times the open circuit voltage multiplied by $\sqrt{3}$ for three-phase circuits. Any calculation of current from generator, line and transformer impedances necessarily omits the factor of the magnetic energy of the line. It is a matter of experience, however, that when the line on which the short circuit occurs is in parallel with other lines of a system, the duty on the switch opening the short circuit is lighter than when the line is not so connected, showing that in such a case the line magnetic energy is not expended in the oil switch tank. In some applications the magnetic energy of the line, however, is a great factor in determining the size of oil switch required. The advantages of the arc kva. system of oil switch rating are that it gives a rating independent of the sizes or characteristics of the generators or other apparatus and independent of the location of the oil switch in the system.

Due to increased current-limiting effect of generator and line impedances, oil switches can be safely rated up when used on voltages lower than their rated voltage, and in making circuit-breaker application, manufacturers' guarantees should be obtained at the service voltage to be used.

The problem of choosing an oil switch or circuit breaker of sufficient rupturing capacity for a given location is, then, to determine the kva. that can be delivered on short-circuit through the circuit breaker. For use with most rating tables, given in generator capacity, and based on standard assumptions, divide the arc kva. by 6.25 before using the tables.

Calculation of Circuit Breaker Rating.—*Example No. 1.*—Assume a three-phase feeder of No. 0 wire, four miles long, delivering 25 cycle power at 7500 volts, with 18 inches between wires. The resistance of the line is approximately 2.1 ohms per wire. The reactance on 25 cycles with the above spacing is 0.835 ohms. The impedance is, therefore, the vector sum of these values and equals $\sqrt{\text{resistance}^2+\text{reactance}^2}=2.26$ ohms. This is assumed to be a case of a small feeder off a large power system where a short-circuit on the feeder would not pull down the system voltage appreciably. If the short-circuit were on all phases the maximum possible current would be:

$$\frac{\text{volts}}{\text{ohms}\sqrt{3}}=\frac{7500}{2.26\times\sqrt{3}}=1910 \text{ amperes.}$$

At 7500 volts this short circuit capacity of the system amounts to 24,781 ultimate kva., which the switch must rupture at the contact. Applying the reverse of the rule for determining ultimate kva. from the catalog rating, this figure should be divided by 6.25, giving 3965 kva. as the minimum allowable catalog rating of the circuit breaker to be applied.

Example No. 2.—Assume a three-phase transformer bank, made up of three single-phase, 200 kva. transformers having 3.5 per cent. reactance and rated at 11,000 volts high tension and 2200 volts low tension, feeding a 2200 volt line from a high capacity power line. It is desired to determine the size of circuit breaker located on the feeder just beyond the transformer bank that will handle when operated automatically, a short-circuit on the feeder just beyond the circuit breaker. Here the transformer bank is the limiting feature. The actual power that can pass through the bank is,

$(100\times\text{transformer kva. rating})\div\text{per cent. reactance}=(100\times3\times200)\div3.5=17{,}100$ kva.

The breaking capacity required is therefore, $17{,}100\div6.25=2730$ kva.

Example No. 3.—Two 18,000 kva., three-phase, 8800 volt generators of six per cent. reactance have a bus section from which a 22,000 volt transformer bank of 2000 kva. per phase and three per cent. reactance feeds out to a circuit breaker. What size of automatic overload instantaneous-trip circuit breaker is necessary to break a short-circuit on this feeder?

TABLE 50.—OIL SWITCHES FOR USE WITH SWITCHBOARDS (GENERAL ELECTRIC REVIEW, MARCH, 1914)

Rupturing Limits of Type "F" General Electric Oil Switches.—Since it is obviously impossible to define limits of capacity which are applicable to every installation, the ratings given in these tables are based on the assumption that the switch will be connected directly to the buses and will be subject to maximum short circuit conditions. If, however, an intervening transmission line or transformer introduces sufficient reactance or resistance in the circuit, or if the generators have favorable short circuit characteristics, the switch can be given a much higher rating. Doubtful cases should be referred to the manufacturer with complete information, including system of connections, size and characteristics of apparatus and line. Definite recommendations will then be secured. Class "A" Systems—All systems excepting those in Class "B." Class "B" Systems—Systems in which one or more generating units are turbo-driven, the reactance of any one of which with its connections to the buses is less than 8 per cent.

Switch			Kva. Rating of Bus Including Overloads of One Hour or More			
			Non-Automatic or Automatic with Time Limit Relays Set to Trip in not Less than 2 Seconds			
Form	Volts	Amperes	Class A	Class B	Class A	Class B
Up to and including 750 volt three-phase systems †						
K13		200	5200	4200	2600	1500
K5	600	300–500–800	5200	4200	2600	1500
K5	4500–7500	200–300–500	11000	9000	5200	3000
K12		1200–1500–2000	17000	13500	8800	4600
K12		300–500–800	21000	17000	11000	5600
K24	600	3000	20000	16000	12000	6100
H3	4500–7500	300–500–800–1200–2000	Above 21000	Above 17000	Above 12000	Above 6100
751 to 2500 volt three-phase systems †						
K13		200	2600	1700	2600	1500
K5	4500–7500	200–300–500	11000	9000	5600	3000
K12		1200–1500–2000	15000	12000	8000	4200
K12		300–500–800	20000	16000	9800	5200
H3		300–500–800–1200–2000	70000	56000	52000	27000
H6		300–500–800–1200–2000–3000–4000	70000	56000	70000	46000
2501 to 4500 volt three-phase systems †						
K5	4500–7500	200–300–500	8400	6700	4200	2200
K12		1200–1500–2000	15000	12000	8000	4200
K12		300–500–800	18000	15000	9100	4800
H3		300–500–800–1200–2000	70000	56000	52000	27000
H6		300–500–800–1200–2000–3000–4000	70000	56000	70000	46000
4501 to 7500 volt three-phase systems †						
K5	4500–7500	200–300–500	7000	5600	3500	1900
K12		300–500–800–1200	15000	12000	8000	4200
H3		300–500–800–1200–2000	70000	56000	52000	27000
H6		300–500–800–1200–2000–3000–4000	70000	56000	70000	46000

7501 to 15,000 volt three-phase systems †

K12	15000	300–500–800	11000	9000	5600	3000
H3	15000	300–500–800–1200–2000	70000	56000	52000	27000
H6	15000	300–500–800–1200–2000–3000–4000	70000	56000	70000	46000

15,001 to 110,000 volt three-phase systems †

K12	22000	300	8700	7000	4400	2300
K21	22000	300–500–800	28000	22000	17500	9400
K22	22000	300–500–800	28000	22000	17500	9400
K24	35000	300	20000		12000	
K21	45000	300–500–800	40000		20000	
K22	45000	300–500–800	40000		20000	
K21	70000	150–300–500	50000		25000	
K22	70000	150–300–500	50000		25000	
K21	110000	100–300	50000		25000	
K22	110000	100–300	50000		25000	
H3	35000	300–500	70000	56000	52000	27000
	45000	300	70000		52000	
	60000	300	70000		52000	
	70000	100	70000		52000	
K15	70000	150	70000		52000	
K15	110000	100	70000		52000	
H6	15000	300–500–800–1200–2000–3000–4000	70000		70000	46000
H6	35000	300–500–800	70000		70000	
	45000	300–500	70000		70000	
H6	60000	300–500	70000		70000	
	70000	300	70000		70000	

† For single-phase multiply above by 0.75; for quarter-phase multiply above by 1.50; for single-phase switches to three-phase buses use three-phase ratings; for switches used on line voltages less than that for which ratings are given, use kva. capacity corresponding to nearest voltage rating; the capacity of switches for intermediate voltages may be obtained by proportion. Remote control switches are recommended for voltages above 3300 and K13 oil switch for circuits 751–3300 volts.

The use of the K13 oil switch on circuits of 751 to 3300 volts, inclusive, is subject to the following limitations irrespective of the bus capacity of the station.

1. It is not to be used for railway service.

2. It is not to be used anywhere on a system, the maximum capacity of which exceeds 20,000 kva. (except as outlined in Clause 6) or in the line of any system subject to severe voltage disturbances.

3. It is not to be used anywhere in a generating station whose maximum capacity exceeds 2600 kva.

4. For systems 2600 to 5600 kva. maximum generating capacity, it may be used in substations, providing a higher duty switch is interposed between it and the main station bus.

5. For systems of 5000 to 20,000 kva. maximum generating capacity, it may be used only under the following conditions:

(a) In a substation, providing transformer capacity not exceeding 750 kva. is interposed between the K13 switch and the line.

(b) On a substation feeder, providing a higher duty switch is interposed between the K13 switch and the substation bus.

6. When considering switches for connection to buses fed from the low-voltage units of motor-generator sets, the capacity of the system supplying energy to the motor-generator sets need not be considered. In such cases the sum of the rated capacities of the generator units of the motor-generator sets must needs come within the limits given in the above table to allow the use of the K13 switch.

A Form H switch is one for mounting in cells of masonry.

A Form K switch is one designed primarily for mounting on pipe framework. It has a removable iron cover.

As the transformers in example No. 2 are near the generators, the capacity of any other synchronous apparatus can be disregarded, assuming that the capacity of all such synchronous apparatus is not more than that of these generators and that they are on the line side; but the combined reactance of the transformers and generators should be included in the computations. As the reactances given are at different capacities, they should be computed in terms of equivalent reactance at the same kilovolt-ampere capacity. Thus the generators (two at 18,000 kva. each) have a capacity of 36,000 kva. through 6 per cent. reactance, and the three 2000 kva. transformers through 3 per cent. reactance have an equivalent capacity of 36,000 kva. through 18 per cent. reactance. The total reactance of the generator and transformers (that which governs the short-circuit current in this problem) is therefore 24 per cent., with a total capacity of 36,000 kva.

As in example No. 2, the actual power that can pass through the circuit breaker upon a short-circuit at this point is therefore:

$$\frac{100\times 36{,}000}{24}=150{,}000 \text{ kva., and this corresponds to either}$$

$$\frac{150{,}000\times 1000}{22{,}000\times\sqrt{3}}=3940 \text{ amperes per line at } 22{,}000 \text{ volts in the arc,}$$

$$\text{or } \frac{150{,}000}{6.25}=24{,}000 \text{ kva. rated breaking capacity.}$$

This is approximately 70 per cent. of its maximum voltage. Therefore, the circuit breaker will have to open 70 per cent. of 150,000 kva., or 105,000 kva. per line at 22,000 volts. This corresponds to either

$$\frac{105{,}000\times 1000}{22{,}000\times\sqrt{3}}=2760 \text{ amperes per line at } 22{,}000 \text{ volts in the arc,}$$

$$\text{or } \frac{105{,}000}{6.25}=16{,}800 \text{ kva. rated breaking capacity.}$$

Before choosing a circuit breaker it should be noted that the voltage necessary is 22,000 volts, or more, and the ampere capacity must be at least

$$\frac{\text{transformer kva. capacity}\times 1000}{\text{volts}\times\sqrt{3}}=\frac{6000\times 1000}{22{,}000\times\sqrt{3}}=157 \text{ amp.}$$

Simplified Method of Figuring Breaking Capacity.—Where the regulation of the circuit at the point where the circuit breaker is to be installed is known or can be accurately computed or measured (in case of a system already installed) the following formula may be used:

$$\text{Approx. short-circuit current}=\frac{(100+\text{per cent.regulation})\times\text{full-load current}}{\text{per cent. regulation}}$$

When the per cent. regulation used in the above formula is the actual regulation at the point at which the circuit breaker is to be installed, taking into account the voltage drop in the generator, all transformers, the line and all other apparatus on the circuit on the power side of the breaker, the result will be correct for that whole system, for:

At no-load the voltage is 100 per cent. plus the per cent. regulation. Full-load current reduces this voltage by the amount of "regulation." Twice full-load current reduces it by twice the amount of "regulation" and so on. The current at which the voltage will be reduced to zero, that is, the short-circuit current, will therefore be:

$$\frac{(\text{Full-load voltage} + \text{regulation}) \times \text{full-load current}}{\text{regulation}}$$

For figuring complex parallel circuits it is best to reduce percentage reactances to ohms by the rule (line volts × per cent. reactance = full-load current × reactance in ohms), as this method admits of easy mathematical solution.

When a circuit breaker is beyond a transformer whose capacity is not over 10 per cent. of the system capacity in synchronous apparatus, it is safe to omit all factors except transformer reactance in figuring short-circuit current through the circuit breaker.

Use of Air-Break Switches.—Opinions differ on the use of air-break switches in the circuits of extensive transmission systems and on the effect of the disturbances which may be caused by them. The following results which were secured from 250 tests,* made with different designs of air-break switches available on a large transmission system in Georgia, provide valuable information when considering the installation of these switches. These tests were made primarily for the purpose of studying the effect of operating air-break switches at different loads and voltages from 50,000 to 110,000 as compared with breaking the circuits through oil switches and to determine the arcing characteristics of the switches available for use. True energy loads were interrupted in one set of tests and the charging current of about 180 miles of transmission line in others. In the latter case a maximum load of 28 amp. at 50,000 volts or 2400 kva. of leading power factor was handled. Oscillograph records were made of the different tests on the switches. From the performance data thus collected the results were formulated.

Operation of Air-Break Switches.—It was found that the maximum time required to break the arc in the 50,000-volt tests was twenty-five seconds, minimum time two seconds, and average time six seconds. This time depended more upon the weather conditions than on the kva. load on the lines, the velocity of the wind being the most important factor. The maximum time required to break the arc at 110,000 volts was sixteen seconds, minimum time, three seconds, and average, seven seconds. This seems to indicate that the air-break switch requires about 120 to 1500 cycles in which to interrupt the circuit, while the oil-break switch may accomplish the same result in a few cycles. This time element in the case of the air-break switch produces an effect in the line similar to a series of light hammer blows. These blows, while not so violent as the one caused by an oil switch, probably have a damaging effect on insulation. It was found that a true energy load was more easily interrupted than a charging current of the same kva. value under the same weather conditions. Under light loads, high winds of about 50 miles per hour materially aided in breaking the arcs by sweeping them from the horns. With heavier loads, however, or lower wind velocities the arcs would lap over the phases and trip the breakers at the power house before they would let loose from the horns or blades.

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* *Electrical World*, October 16, 1915, pages 853 to 855.—Arcing Characteristic of Air-Break Switches, by Charles E. Bennett.

The results of the tests showed that the minimum distance between the phases for 44,000 volts should be at least 7 ft. and for higher voltages proportionately more. The 70,000-volt switch used was spaced 6 ft. between phases and the 44,000-volt switches 4 ft. The theory that the heat of the arc alone will carry it up the horns is doubtless well founded, but this force is only great enough to accomplish this result when the air is perfectly still. With the slightest wind blowing, the arcs are blown sidewise, and the tendency of the arc to rise is more or less counteracted by this horizontal wind pressure. If, however, the mechanical movement is such as to draw the arcs up the horns, the tendency to rise is increased and it is much easier then to break the arc. The arc appears to be an uncontrollable feather-like medium, and but a slight wind will blow it 8 ft. or 10 ft. horizontally.

Switching Disturbances.—The oscillograph records made showed that there is a considerable disturbance caused on the line evidently due to the charging and discharging of the line as a condenser when operating air-break switches. Harmonics are set up on the regular sine wave, but, owing to the high frequency, oscillations are not clearly shown by the oscillograph. This is probably due to the fact that the transformers used in stepping down the voltage for the instrument absorbed these surges. In order to get a better check on the voltage rise on the load side of the switch, a needle spark-gap was connected and set at 5, 6, 7 and 8 in., or for about 63, 72, 80 and 87 kv. The circuit was broken under different loads with the different types of switches, and the points were set at these distances when the maximum sparking distance was noted. The circuit was then interrupted with an oil switch, under similar conditions and loads, and it was found that the sparking distance was greater than with an oil switch under the same load. This is contrary to some opinions on the subject.

This experiment seems to show that the tendency for the lines to spill over the insulators when the system is interrupted with an oil switch is greater than when the air-break switch is used. If air-break switches are to be used to sectionalize only short lines, or for cutting in and out a bank of transformers occasionally, or for use in emergency the dangerous effects due to their use are small. Where frequent switching is necessary, the oil switch is undoubtedly much safer.

The chief difficulty in the use of air-break switches is the large amount of space necessary for their installation. The different phases must be widely separated and great care exercised in wiring up the switches so that the arcs of one phase cannot blow against the leads to some other phase and thus short-circuit the line. In some cases the arc is blown downward, and this means that the switches must be well insulated from supporting steel work a distance sufficient to keep the arc from lapping and thus grounding the line.

IV. STRANDED IRON AND STEEL WIRES AS TRANSMISSION LINE CONDUCTORS

Iron and Steel Conductors.—Under normal conditions of the metal market operating companies have employed iron and steel conductors for transmission lines only where small loads were to be transmitted or great strength was required for long spans. High prices of copper and aluminum have, however, caused thorough investigation of the characteristics of iron and steel wires and cables and the formulation of conditions for their economical use. The following results of tests conducted by Messrs. Oakes and Eckley at the Oregon Agricultural College, Corvallis, Oregon, are given as published in the *Electrical World*, October 14, 1916.

The resistance of a conductor carrying an alternating current is affected by the frequency and magnetic properties of the conductor. For non-magnetic conductors the increase in resistance due to skin effect, except for very large conductors, is negligible, but for iron or steel wires the skin effect causes a material increase in resistance. The effect is also cumulative. The permeability increases with the current density within certain limits, and as skin effect is due to a greater self-inductance (a function of the permeability) at the center of the wire than at the surface, an increase in resistance with an increase in current results. Because of the magnetic properties of iron and steel, the computation of the skin effect is rather difficult. Other factors affecting the power loss in a magnetic conductor are the hysteresis and eddy current losses. The effective resistance is a function of all these factors and is a value such that when multiplied by the square of the current it will give the power loss in the line.

The reactance of a conductor composed of a magnetic material is a variable and is composed of two factors: the external reactance, which is easily computed, and the internal reactance, which is a function of the permeability. Due to the fact that permeability depends not only on the current density, but also on the physical properties of the material, the internal reactance cannot be computed accurately unless a permeability curve is at hand. It should also be noted that the internal reactance is due to circular magnetization, and therefore the permeability for circular magnetization should be used.

The various electrical and magnetic constants for any particular grade of iron or steel wire cannot be given with any absolute degree of accuracy because of the method of manufacture. A slight change in the ingredients of the wire that would not affect the mechanical properties would cause a material change in the electrical and magnetic characteristics. For this reason, unless accurate test data are available, any computations that may be made would necessarily be only approximate.

Characteristics of Iron and Steel Conductors.—The accompanying curves, Figs. 174 and 175, give the internal reactance, alternating-current resistance, power loss and permeability of different sizes and qualities of iron and steel wire that might be used for transmission lines. The data were secured from tests made on wires approximately 1000 ft. in length and spaced 30 in. apart. The internal reactance was obtained by subtracting the computed external reactance from the measured reactance. The following formulas, which are modifications of those by Dwight, give the reactance in ohms per mile of single conductor for the conductors tested:

The reactance at 60 cycles for No. 6 B. W. G. solid B. B. galvanized iron is,

$$X = 0.27941 \log_{10} \frac{D}{0.1055} + X'$$

The reactance at 60 cycles for 5/16-in. seven strand Siemens-Martin or ordinary grade galvanized steel is,

$$X = 0.27941 \log_{10} \frac{D}{0.0545} - 0.09865 + X'$$

The reactance at 60 cycles for three strands of No. 10 B. W. G. B. B. grade galvanized iron is,

$$X = 0.27941 \log_{10} \frac{D}{0.144} - 0.0371 + X'$$

In these formulas, X is total reactance in ohms per mile of line; X' is internal reactance from curve; D is spacing in inches.

The inductance of a seven-strand cable of a non-magnetic material as given by Dwight* is,

$$L = \frac{1}{49}\left(98 \log_e \frac{S}{r} + \frac{7}{2} - 24 \log_e 2 - 60 \log_e 2 - 12 \log_e 6\right) \text{ per cm.}$$

For a three conductor cable the formula is,

$$L = 2 \log_e \frac{S}{2.153r} + \frac{1}{6} + 2 \log_e \left(\frac{2\sqrt{3}+3}{3}\right) - \frac{4}{3} \log_e 2 \text{ per cm.}$$

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* Reactance of Stranded Conductors, by H. B. Dwight, *Electrical World*, Vol. 61, No. 16, page 828.

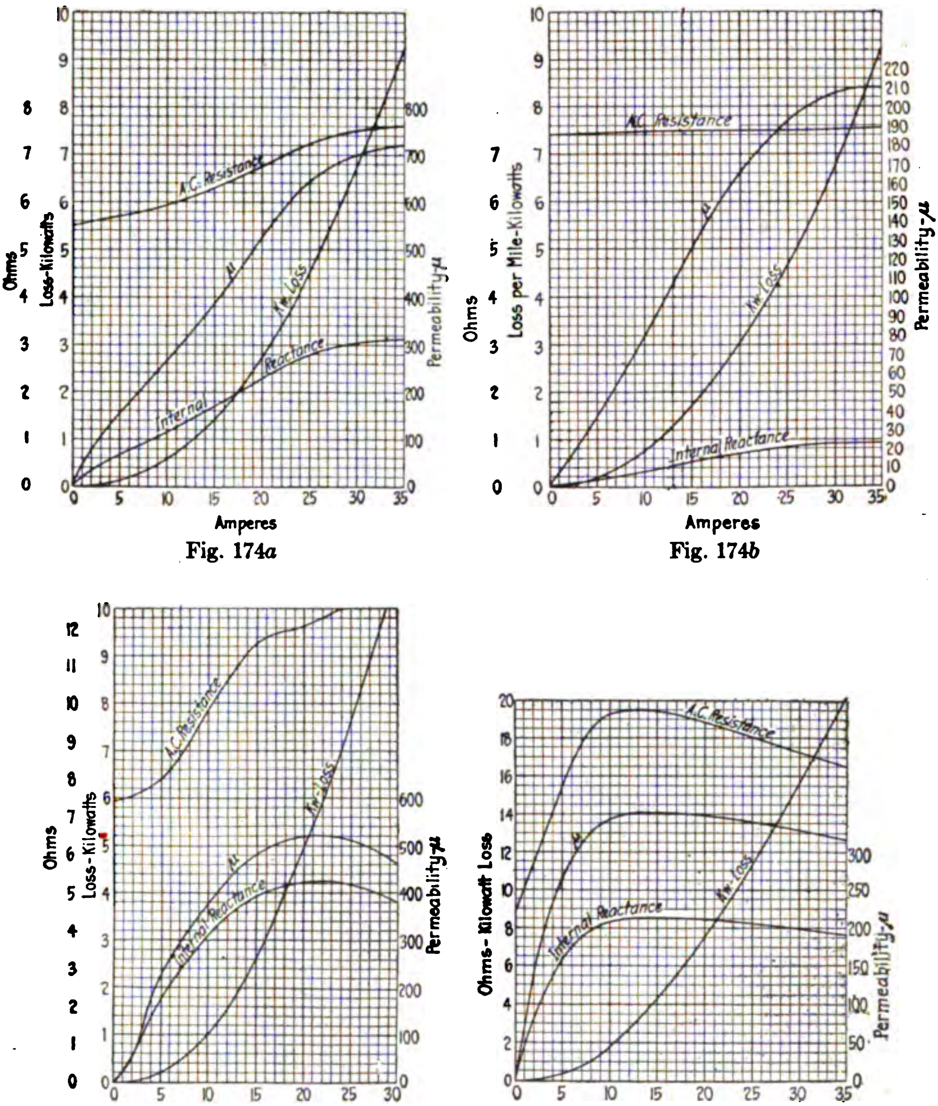

Fig. 174*a*

Fig. 174*b*

Fig. 175*a*

Fig. 175*b*

Figs. 174 and 175—Constants for One Mile of 7-Strand Steel and 3-Strand Iron Wire at 60 Cycles and Temperature of 20 Deg. C. and for No. 6 B.W.G.-B.B. Solid Galvanized Iron Wire at 60 Cycles and Temperature of 20 Deg. C.

Note: The curves in Fig. 174*a* are for a 7-strand $\frac{5}{16}$ in. ordinary galvanized steel cable; those of Fig. 174*b* for 7-strand $\frac{5}{16}$ in. Siemens-Martin galvanized steel cable and those of Fig. 175*a* for 3-strand No. 10 B.W.G.—B.B. galvanised iron wire. The curves of Fig. 175*b* are for No. 6 B.W.G.—B.B. solid galvanised iron wire.

In these formulas, L is inductance in cm.; S is spacing; r is radius of each strand in the same units as S.

These formulas are based on the assumption that the current density in each wire making up the cable is uniform and that the wires, so far as the mutual inductance of one on the other is concerned, are replaced by very small conductors located at the center of the strands of the cable. Considering a magnetic conductor a slight modification in the above formulas must be made, namely, the permeability factor μ must be introduced into the term for the internal inductance. The following formulas would then apply:

For a seven-strand cable,

$$L=\frac{1}{49}\left(98 \log_e\frac{S}{r}+\frac{7\mu}{2}-24 \log_e 2-60 \log_e 2-12 \log_e 6\right) \text{ per cm.}$$

For a three-strand cable,

$$L=2 \log_e \frac{S}{2.153r}+\frac{\mu}{6}+2 \log_e \left(\frac{2\sqrt{3}+3}{3}\right)-\frac{4}{3} \log_e 2 \text{ per cm.}$$

The terms involving the mutual inductance of the wires are not affected, since the medium separating the strands, the zinc galvanizing, has a permeability of unity. These formulas are fairly accurate so long as the skin effect is practically negligible. For small wires, below No. 14, this condition holds. For large size, however, an error is introduced.

The data for the permeability curves were obtained by solving the above equations for μ. The permeability for the No. 6, B. W. G. B. B. solid galvanized iron wire of Fig. 175, was obtained by substituting test data in the following formula taken from the "Standard Handbook for Electrical Engineers" (fourth edition, Article 77, Section 2):

$$L=0.1403 \log_{10}\frac{D}{r}+0.01524\mu,$$

in millihenrys per 1000 ft.

In lieu of other data, these permeability curves may be used to compute with a fair degree of accuracy the inductance of other sizes of cables of the same material. Particular attention is called to the fact that current density must be used as a basis for comparison. The relative size of wire with respect to the size for which curves are given has a direct bearing on the accuracy obtainable. The nearer the size of wire under consideration is to the size for which curves are given, the greater will be the degree of accuracy. The error is due to the fact that for the same current density the skin effect is not the same in different sizes of wire. An error would also be introduced because, as noted previously, iron and steel wire is not well standardized.

The resistance and loss curves were taken from test data, all values being corrected to a temperature of 20 deg. C. A temperature coefficient of

0.0053 was used both for iron and steel. The value of resistance given for zero amperes is the direct-current resistance corrected to 20 deg. C. These curves substantiate the results of other observers in that in each case the resistance and internal reactance increase with the current until a maximum is reached, when a further increase in current causes a decrease in effective resistance and reactance. The explanation lies in the fact that as the iron becomes saturated, the eddy current and hysteresis losses do not increase with an increase in current. It should be noted that the rate of increase of resistance is different for the different grades of wire, the softer grades showing the greater increase.

Selection of Iron Wire for Transmission Purposes.—In the selection of an iron wire for transmission line purposes, a great many varieties present themselves for consideration. Other electrical factors remaining the same, the wire to be selected should have a high conductivity and a relatively low first cost. Table 51 gives the cost, resistance and area in circ. mil of the stranded wires, the constants for which are shown in Figs. 174*a*, *b* and *c*. In order to compare them on a basis of equal area, the resistance of three strands of B.B. galvanized iron of an area equal to the seven strand cables was computed. In view of the fact that the resistance of grade B.B. wire increases more rapidly than the resistance of ordinary grade steel, it is evident that of the three wires enumerated in the table below, the ordinary grade steel would be the most economical if first cost, operating cost during the life of the wire, etc., are taken into consideration.

TABLE 51.—COST, RESISTANCE AND AREA IN CIRC. MILS OF STRANDED WIRES CONSIDERED

MATERIAL	AREA IN CIRC. MIL	DIRECT-CURRENT RESISTANCE PER MILE	*COST PER MILE
Three-strand B. B. galvanized iron	83,167	4.78	$103.00
Seven-strand Siemens-Martin galvanized steel	83,167	7.41	95.60
Seven-strand ordinary grade galvanized steel	83,167	5.51	79.20

* Pacific coast prices (1916).

Steel vs. Copper for Conductors.—The data of the accompanying table comparing steel and copper transmission line costs is based on a particular set of conditions and illustrates the considerations that are involved when deciding upon the economy when using steel conductors. The case is made general by assuming certain values of line current and considering that a copper wire smaller than No. 6 cannot be used for mechanical reasons. In general it may be said that steel conductors can be used economically when the price of copper is high (more than 30 cents per lb.) for the transmission of small loads and where a copper conductor having the necessary conductivity would not meet mechanical requirements. Each case,

TABLE 52.—COMPARATIVE STEEL AND COPPER TRANSMISSION LINE COSTS

GENERAL CONDITIONS AND ASSUMPTIONS			
Conductor:		Salvage value of copper	8 cents per pound
Steel—5/16 in.—seven-strand ordinary grade galvanized.		Salvage value of steel	None
Copper—No. 6 H. D. copper, 96.2 per cent. conductivity.		Cost of power	0.5 cents per kilowatt-hour
Length of line	10 miles	Interest on investment	5 per cent.
Useful life of line	Twenty years	* Cost of stringing wires (three wires) per mile of line:	
Number of phases	Three	Steel weight per single conductor, 1107 lb.; per mile	$53.50
Length of span	Same for both cases	Copper weight per single conductor, 20 lb.; per mile	$26.20

STEEL CONDUCTORS		COPPER CONDUCTORS	
Fixed charges:		30 miles No. 6 H. D. copper at 36 cents per lb.	$4,536.00
30 miles of wire at $70 per mile	$2,100.00	Stringing wire, three conductors at $26.20 per mile	262.00
Stringing wire at $53.50 per mile of line	535.00	Interest on investment at 5 per cent., twenty years	4,798.00
Interest on investment at 5 per cent., twenty years	2,635.00		
			$9,596.00
Total	$5,270.00	Less salvage value at 8 cents per pound	1,008.00
			$8,588.00
Variable charges		Variable charges	
Energy loss twenty-four hours per day, 360 days per year at 0.5 cent per kilowatt-hour.		Energy loss twenty-four hours per day, 360 days per year at 0.5 cent per kilowatt-hour.	
Line current 1 amp. (Resistance 5.51 ohms per mile)	142.75	Line current 1 amp.	56.25
Line current 2 amp. (Resistance 5.58 ohms per mile)	578.90	Line current 2 amp.	225.00
Line current 5 amp. (Resistance 5.72 ohms per mile)	3,706.55	Line current 5 amp.	1,406.25
Line current 7 amp. (Resistance 5.8 ohms per mile)	7,366.45	Line current 7 amp.	2,756.25
Line current 10 amp. (Resistance 5.95 ohms per mile)	15,422.20	Line current 10 amp.	5,625.00
Total cost at end of useful life of line:		Total cost at end of useful life of line:	
Line current 1 amp.	$5,412.75	Line current 1 amp.	$8,644.25
Line current 2 amp.	5,848.90	Line current 2 amp.	8,813.00
Line current 5 amp.	8,976.55	Line current 5 amp.	9,994.25
Line current 7 amp.	12,636.45	Line current 7 amp.	11,344.25
Line current 10 amp.	20,692.20	Line current 10 amp.	14,213.00

* Based on data used by Oregon commission

however, is a special problem in itself and must be so considered. The steel conductor has also the advantage that its greater mechanical strength permits a longer span, providing that no appreciable increase in load is contemplated, otherwise the length of span must be such that ultimately a copper conductor may be substituted.

V. INSULATOR SELECTION AND TESTING

Insulator Troubles.—The real causes of insulator depreciation and failure have not as yet been definitely discovered, although methods are now being employed with success to reduce failures which have as their aim the selection of designs suited to line characteristics and the subjection of all units to a uniform quality test. The troubles with insulators are varying in character. It has been found that voltages many times normal are impressed on insulators in many cases. One case has been reported where one section of a 63-mile, 22,000-volt line was insulated with two suspension insulators in series which required not less than 180,000 volts to flash over. In several instances these strings have flashed over when the operating voltage was not more than 23,000. It is now evident that there are factors other than the normal line voltage which are important in determining the size and kind of insulator to use. It is being more and more recognized that the amount of power applied to the line, the length of the line and the size of the wire are as important features as operating voltage.

The testing of insulators has received much study and investigation work along new lines has been conducted in recent years with the result that some of the manufacturers are now offering insulators which very satisfactorily stand severe tests, both mechanical and electrical. The testing of insulators with high-frequency test transformers, however, is comparatively new and has not yet received the sanction of all of the insulator manufacturers or the official sanction of the American Institute of Electrical Engineers. It is noted, however, that as the manufacturers improve their product so that insulators will stand the oscillation transformer test the objections to its use are less frequent.

One of the great advantages of this method of testing is that it can be standardized for both the maker and the user. Operating companies cannot, in general, equip testing departments with sixty-cycle transformers for insulator testing which will give the necessary high voltage, and it is out of the question to use these large transformers at the various distributing points. The oscillation transformer, however, can be set up in a stock room or used by line crews, the insulators being tested immediately before they are placed on the line. The best reason for the use of the oscillation transformer is that it will detect faulty insulators which cannot be weeded out by a sixty-cycle test.

High Frequency Testing.—Results of a careful study of insulator failure on some 300 miles of transmission lines operating at 11,000, 22,000, 66,000, and 110,000 volts and using a large number of different types of insulators have been reported by one investigator,* with special reference to the value of the high frequency test. Tests with an oscillation transformer giving a frequency of approximately 200,000 cycles showed a great difference in the performance of insulators. It was noted that some insulators which had been giving trouble on the line owing to the inner petticoats breaking showed a definite corona around these petticoats at a voltage much below the flash-over voltage. In fact, on some insulators the inner petticoat could be made to flash almost continuously without flashing over the outer petticoat. It was noted, also, that other insulators showed very little corona previous to the flash-over of the insulator. Some of the insulators showing this characteristic have given excellent results in service.

Service results observed have shown that an insulator, or string of insulators, which has a high ratio of puncture voltage under oil to flash-over voltage in air is necessary. There has been some objection to taking this ratio as one of the points of value in an insulator, the objection made to the puncture value under oil being that the electrical stress on the different parts of the insulator is very largely changed by the oil bath. However, the electrical strength of the porcelain cannot be determined in an insulator unless the discharge over its surface is prevented. It is also necessary that the voltage strain which is applied to the insulator when it flashes over must be very much below the puncture voltage of the insulator. If this is not the case, the insulator will be weakened by continuous application of flash-over voltage and will finally fail. One of the objections raised to the oscillation transformer test is that it can be made so severe that perfectly good porcelain will be broken down. The opinion of this investigator and others, based on test results, is that if an insulator is properly designed and the porcelain sufficiently good no damage will be done to the insulator by any tests which can be applied with a 300,000-volt oscillation transformer.

As a result of the tests referred to, it has been decided to fix the voltage of an oscillation transformer for use on the line at about 150 kva. and to apply flash-over voltage from this transformer to all insulators for five seconds. This is a routine test now used by the Georgia Railway and Power Company and applied to all new insulators before they are installed on the line. It is also applied to all old insulators, which are taken down before they are used again. An attempt is also made to duplicate the line conditions in the laboratory by applying strain, vibration, temperature-change and electrical tests. One of these tests or some combination of them when applied to the insulators will determine, in a few days in the laboratory, the insulator which will stand most satisfactorily several years of service on the line.

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* *Electrical World*, Nov. 13, 1915.—"Insulator Performance from Operating Viewpoint, and Tests to Weed out Defective Units," by E. P. Peck, Georgia Railway and Power Company.

Insulator Failures on Lines.—Mr. Peck has found that some insulators which stand all electrical tests satisfactorily when new show a large percentage of failures after having been installed on the line for some years. Some of the old insulators fail through the inner petticoat, some through the head of the outer petticoat, some puncture entirely through the head when test voltage is applied, while others fail, due to cracking around the tie-wire groove. Suspension insulators often have skirts broken on account of the arc playing over these parts after the initial flash-over. This trouble is largely eliminated if the insulators are very closely spaced, that is, if the string length is as short as possible and some form of arcing horn provided.

The extremely high voltage which is produced on lines is undoubtedly due to high-frequency disturbances, as these disturbances are produced on circuits having appreciably high capacity and reactance and are nearly always caused in the first place by an arc to ground. It is very probable that in some cases the shape of the voltage wave is very similar to that produced by the oscillation transformer. In most cases of extremely high voltage the wave shape of the voltage probably approaches much nearer to that of the oscillation transformer than it does to the line voltage. If this is the case and the insulators receive these abrupt-wave-front, high-frequency impulses on the line, it is logical that a test giving a voltage of this nature should be applied to them as a part of the initial tests before they are installed on the line.

Locating Leaky Insulators on Line.—Leaky insulators can be located while a line is in service by testing with telephone receivers. For this test a pair of high-resistance receivers are connected from a spike driven about shoulder high in the pole to another spike driven in the ground. The noise produced in the telephone receivers to the trained ear gives a good indication of the condition of the insulators. By this test any insulator that is approaching a dangerously weakened condition can be detected.

VI. TRANSMISSION LINE TELEPHONE TROUBLES

Telephone Circuits Paralleling High-Voltage Lines.—When telephone lines parallel transmission lines and are carried on the same supporting structures, certain construction and protective requirements have been found necessary in order that reliable communication may be maintained at all times and especially in lightning storms and during other equipment disturbances. The first requirement in this connection is high insulation, for the telephone lines, the second, carefully balanced transposition, the third, adequate drainage provisions, and the fourth the best possible character of protection for telephone terminal apparatus. Considerable study has been given to these features and practical measures are now being adopted which make it possible to maintain reliable telephone service under all operating conditions. The most elaborate study of the subject and one of the best examples of good practice has been carried out and adopted for the system of the Georgia Railway and Power Company of Atlanta, Ga. The following details are given for the construction used and special protective apparatus devised by E. P. Peck,* Electrical Engineer of this company.

Telephone Line Insulation.—It has been found necessary to insulate the telephone lines of the Georgia Railway & Power Company paralleling 110,000 volt transmission circuits from Atlanta to Tallulah, Ga., with two suspension insulators in series, which provide sufficient insulation for a working voltage of 22,000. This high insulation is necessary to prevent puncture to the insulators at times of lightning storms or transmission line disturbances. It is also necessary to prevent leakage over the insulators which would cause the line to become unbalanced and noisy.

Balanced Transposition.—This is necessary to prevent an induced voltage between the two telephone lines. The power line will necessarily induce a high voltage from the telephone lines to ground, but the voltage between telephone lines must be maintained at a low value.

Drainage Requirements.—On telephone lines, which closely parallel for a long distance high voltage power lines, a voltage from the telephone line to ground of several thousand volts will be induced. If the telephone line is grounded, a current of several amperes will flow through the ground connection. Drainage coils to be effective, therefore, must be of sufficient capacity to carry the line charge to ground continuously. On the 110,000 volt telephone lines of the Georgia Railway & Power Company 15 kw., 2200-volt standard distribution transformers are used as drainage coils. The 2200-volt leads are connected to the telephone lines and the middle point of the 2200-volt winding is grounded. The secondary leads are, of course, open. These drainage coils are protected by cylinder gaps set 0.2 in. from each line to ground and by 25 amp. high voltage expulsion fuses on the line side of the ground gaps. The drainage coils and their protective equipment are installed outside of the building. A few disturbances have blown the drainage coil fuses violently, but no damage has ever been done to the drainage coils.

Telephone Protection.—The type of lightning arrester described in what follows and shown in the illustration as developed by E. P. Peck has in its several forms during the past two years (1915-1916) rendered practically complete protection to telephones and operators under all conditions. The different sizes of lightning arresters were so made and insulated that if full transmission line voltage be impressed on them from either the line to line connection or a line to ground connection, no damage could be done to the telephone arrester or the telephone equipment. This is a severe requirement, but the position was taken that a mistake in insulating the telephone line for too low voltage does not justify under-insulation on the telephone lightning arrester. The point has been brought up that it is unnecessary to insulate the telephone arresters for a higher flash-over voltage than is provided for on the telephone line insulators. The designer claims, however, that the arrester should be safe and should function properly regardless of the performance of the rest of the line. This requires that auxiliary protection be put outside the building entrance and that all telephone lines from this entrance to the top of the arrester be insulated for the full voltage which the auxiliary gaps may allow to pass.

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* *Electrical World*, Sept. 9, 1916.—"Eliminating Transmission Line Telephone Troubles," by E. P. Peck.

Construction of Arresters.—Three sizes of telephone arresters have been designed and for convenience are designated as *P-A*, *P-B* and *P-C*. The essential features of these designs are shown in the accompanying diagrams. The *P-A* construction is for use on ordinary telephone lines where good protection is required. By ordinary lines is meant lines which are not subject to crosses with lines having voltages higher than 2500. The *P-B* arrester is designed for use on telephone lines which are liable to be crossed with power lines having voltages up to 35,000 volts. The *P-C* arrester is designed for use on telephone lines which may be crossed with lines of any voltage higher than 35,000, the limit of the arrester being the limit of the transmission voltage; that is, the arrester is designed and will properly function on 100,000 and 150,000-volt lines. Any of the arresters will give good protection to the telephone in cases of ordinary lightning trouble.

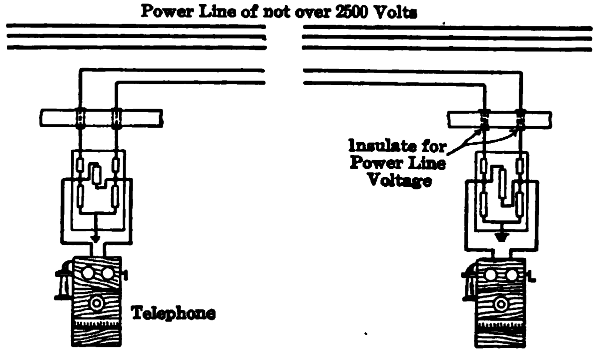

Power Line of not over 2500 Volts
Insulate for Power Line Voltage
Telephone

Fig. 176.—Construction and Connections for Peck Arrester Designed for Use Near 2500 Volt Power Lines

The *P-A* arrester consists of vacuum gaps connected as shown in Fig. 176, with fuses between the vacuum gaps and the incoming telephone lines. These fuses should not have a rating of over 7 amp. or less than 5 amp. The base of the arrester is made of a very high grade insulating material, and if the incoming lines and arrester are insulated from the walls and surrounding objects by mounting on ordinary porcelain knobs, the arresters will afford protection up to the limit specified. Since the class of telephone lines which this arrester was designed to protect do not, ordinarily, operate at a high voltage to ground and are not subjected to continuous high voltage, the arrester has been made very simple without reducing its effectiveness as regards lightning protection.

The *P-A* arrester was designed primarily for use at the junction of overhead lines with telephone cables. In this case it is necessary to hold the voltage from line to ground low as well as to hold the voltage from line to line low. Where a telephone cable is not connected but protection is desired for an instrument at the terminus of the overhead line, a slightly modified form of the *P-A* arrester is satisfactory. This arrester differs from the *P-A* in that it has air spark gaps from each line to ground instead of vacuum gaps. These air gaps will not hold the voltage from line to ground at as low a value as will the vacuum gaps, but will hold it sufficiently low to give satisfactory protection to a telephone instrument under the conditions mentioned here.

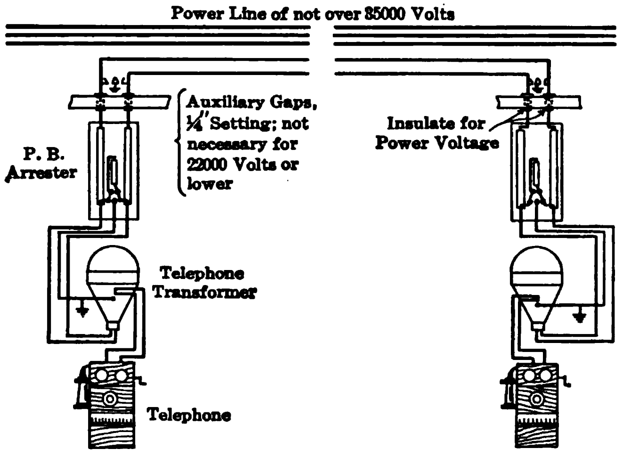

Power Line of not over 35000 Volts
P. B. Arrester
Auxiliary Gaps, ¼" Setting; not necessary for 22000 Volts or lower
Insulate for Power Voltage
Telephone Transformer
Telephone

Fig. 177.—Construction and Connections for Peck Arrester for Use Near 35,000 Volt Power Lines

The P-B arrester shown in Fig. 177 is designed for very much higher voltage lines and for this reason is larger and has the ground gaps adjustable. This adjustment is provided so that for any line the ground gaps can be set for the conditions of that line, in every case being set low enough so that the arrester will discharge in case of any disturbance, but will not be subject to continuous discharges in regular operation.

Ground Gaps and Line-to-Line Gaps.—Any telephone line paralleling a high voltage power line will have a voltage induced between the telephone line and ground. The ground gaps should therefore be adjusted in proportion to this voltage. The probable setting of these ground gaps should be between 1/64 and 1/16 in. The protection to the telephone instrument is provided by a vacuum gap connected from line to line. This vacuum gap is paralleled by a very small air gap which comes into play only in case the vacuum gap has been destroyed by a small but continuous discharge. If it is found at any time that the compound has melted from the bottom of the vacuum gap, this unit must be replaced, as the vacuum is destroyed when the compound is melted, and the discharge voltage of the gap changes from approximately 350 to several hundred volts higher. The designer has found that vacuum gaps are damaged very seldom, but it was thought advisable to provide the auxiliary gaps as an added protection, as the vacuum gaps will sometimes go down. The air gap from line to line is set 0.004 in. and should not be changed.

In the *P-B* arrester all of the protective gaps are themselves protected by 12-in. expulsion fuses connected between these gaps and the line. These fuses should have a capacity of between 5 and 7 amp. The fuses and gaps are mounted on a hinged base so that the working parts of the arrester can be disconnected from the line when it is necessary to replace the fuses or to adjust the gaps. It is recommended that this switch be pulled when it is necessary to work on the arrester.

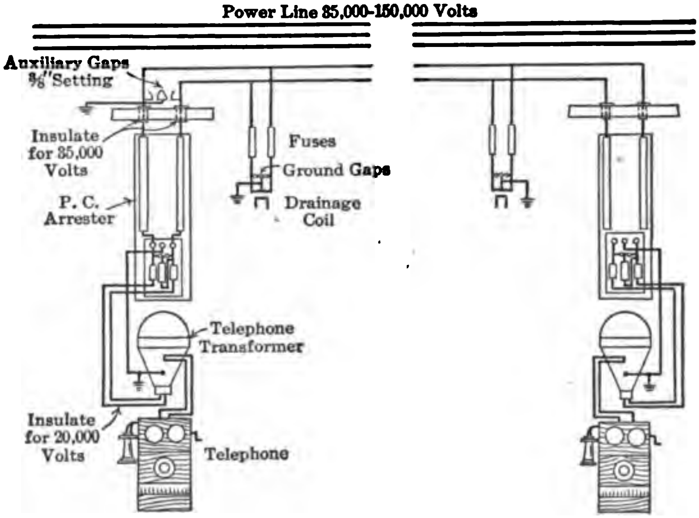

Power Line 35,000-150,000 Volts
Auxiliary Gaps 3/8" Setting
Insulate for 35,000 Volts
P. C. Arrester
Fuses
Ground Gaps
Drainage Coil
Telephone Transformer
Insulate for 20,000 Volts
Telephone

Fig. 178.—Construction and Connections for Peck Arrester Designed for Use Near Power Operating at Voltages over 35,000

Protection Against Dangerous Voltages.—The insulation between the various parts of the arrester is sufficient to stand a continuous application of 25,000 volts and for lines up to this voltage no auxiliary gaps are necessary. When the arrester is used on lines having voltage higher than this, that is, between 25,000 and 35,000 volts, auxiliary horns are necessary. These horns should be placed outside the building and should be connected from line to ground as shown in Figs. 177 and 178. The setting of these auxiliary horn gaps should be 0.25 in.

The wiring from the building entrance to the top of the arrester should be insulated so that a flashover cannot occur from line to line or from line to ground in case of a cross between the telephone line and the power line. That is, in case the telephone line parallels a 25,000-volt power line, the wiring from the cut-in to the arrester should be safe for 25,000 volts when applied from line to line or from line to ground. This is important even if the insulators used on the telephone line are much smaller than those used inside, because a flashover from excessive voltage inside the building is very dangerous.

A telephone transformer, which is insulated for 25,000 volts from primary to secondary, should be used between the telephone instrument and the incoming line on all telephone lines which are subject to crosses with power lines of 6,600 volts or over. It is not recommended that any high-voltage line be operated without this transformer in service, on account of the danger to the person using the telephone. Such telephone lines are liable to become exceedingly dangerous at any time and the protection of this transformer is desirable at all times. The *P-B* arrester should be placed between the telephone transformer and the incoming line to prevent damage to the transformer windings due to excessive voltage from line to line.

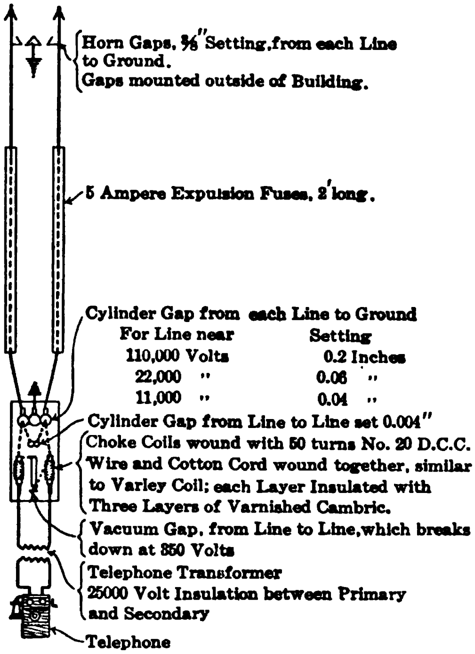

Horn Gaps, ⅜" Setting, from each Line to Ground.
Gaps mounted outside of Building.
5 Ampere Expulsion Fuses, 2' long.
Cylinder Gap from each Line to Ground
For Line near Setting
110,000 Volts 0.2 Inches
22,000 " 0.06 "
11,000 " 0.04 "
Cylinder Gap from Line to Line set 0.004"
Choke Coils wound with 50 turns No. 20 D.C.C. Wire and Cotton Cord wound together, similar to Varley Coil; each Layer Insulated with Three Layers of Varnished Cambric.
Vacuum Gap, from Line to Line, which breaks down at 350 Volts
Telephone Transformer 25000 Volt Insulation between Primary and Secondary
Telephone

Fig. 179.—Essential Construction Features of Peck Telephone Arrester for Use Near Very High Voltage Power Lines

Arrester for 110,000 Volts and Above.—The *P-C* arrester shown in Figs. 178 and 179 is designed to protect telephone lines which parallel power lines of 35,000 volts or higher. That is, the arrester must afford protection to the station telephone apparatus if the telephone line becomes crossed with a power line operating at 110,000 volts, or at a higher voltage. This arrester is similar in principle to the *P-B* design, but has higher insulation and larger fuses. Also choke coils are provided on the telephone side of the discharge gaps. The construction is larger and much more rugged on account of the more severe conditions which are likely to be imposed on the arrester. The fuses are mounted on a hinged frame and are of the expulsion type, 24 in. long. The size of the fuse wire required is 7 or 5 amp. The ground gaps on this arrester are adjustable and should be set so that they do not discharge except in case of disturbance on the line. The setting of the gap will vary from 1/16 to 1/4 in., depending on the voltage from the telephone line to ground. The setting of the ground gap does not determine the protection afforded the telephone instrument. These ground gaps must be set low enough to protect the high-voltage winding of the telephone transformer. It is really not of great importance that these gaps be set low, but it is important that both ground gaps be set the same. The protection to the telephone instrument is given by the vacuum gap and the 0.004 in. air gap, both of which are connected from line to line.

It is essential that this arrester be itself protected by auxiliary ground gaps placed just outside of the building cut-in, and these gaps should be set at approximately 3/8 in. The gaps will afford protection to the inside wiring up to the arrester and to the top of the arrester itself in case of a cross between the telephone line and the power line. The wiring from the building entrance to the top of the arrester should be mounted on insulators which will not flashover at less than 45,000 volts. The wiring from the bottom of the arrester to the telephone transformer should be safe for 20,000 volts. The wiring from the telephone transformer to the telephone instrument may be ordinary telephone wire run through conduits or put up in the regular way. The frame of the telephone transformer should be solidly grounded in all cases.

The setting of the line to ground gaps for the *P-B* arresters are made 1/32 in., when the arresters are used on 11,000 and 22,000-volt lines. The setting of the line to ground gaps on the *P-C* arrester is 0.2 in. when used on 110,000-volt lines. The settings of the line-to-line gaps on all of the arresters of this line are 0.004 in. The discharge voltage of the gaps at these settings is approximately 700 volts for the 0.004 in., 3000 volts for the 1/32 in. and 10,000 volts for the 0.2 in. The vacuum gaps discharge at approximately 350 volts.

Installation and Inspection of Arresters.—The main points to be noted in installation and inspection are as follows: *Horn Gaps:* The horn gaps outside the building should be of heavy material, that is, not smaller than 0.25 in., and these horns should be so located that a continuous heavy arc on them will not damage the building or other equipment. The settings should agree with those recommended for the arrester.

High-Voltage Wiring.—The telephone wiring from the horn gaps to the telephone arrester should be as recommended for each arrester.

Telephone Arrester.—The arrester should be mounted in a clean dry place and should be located so that the violent blowing of the expulsion fuses cannot damage anything. The setting of all gaps should be checked and the condition of the vacuum gaps noted. If the vacuum gap has been damaged from heat, the sealing compound will have been melted and will have run over the small porcelain insulator in the bottom of the gap and perhaps down the stem. This is the first indication of trouble on the vacuum gaps. The condition of all air gaps should be noted, paying special attention to any burning of these gaps or any dirt between them. The fuse wire should not be larger than 7 amp., or smaller than 5 amp. The bases should be examined to see if they have become charred by excessive discharges. The mechanical condition of the arrester should be noted.

Ground Wire.—The ground wire should not be less than No. 8, preferably No. 6, copper wire and should connect to the ground post of the arrester and to the frame of the telephone transformer. The ground itself should be made of not less than two pipes 0.75 in. in diameter and 6 ft. long. The pipes should be spaced 6 ft. apart if practicable. If the pipes are larger or longer than those specified better grounding will be obtained.

Operating Results.—Trouble has been predicted from setting the cylinder gaps between lines as low as 0.004 in., due to the gaps burning together during severe discharges. It has been found, however, that when these gaps are protected by 5 amp. fuses they do not burn together. Very little trouble has been experienced from dust settling in the gaps, although it is necessary to clean them at times.

The 5 amp. fuse has been found to be very satisfactory. It is so large that it does not blow except in cases of extreme trouble; under average conditions these fuses blow only a few times during the year. On the other hand, the fuses are small enough to properly protect the arrester even if blown several hundred times. Some of the first arresters gave trouble due to leakage across the surface if exposed to dust and moisture for a long time. This trouble has been slight, however. Another trouble has been that a very slight continuous discharge through the vacuum gap will in time burn out the vacuum gap, allowing the voltage across the telephone terminals to rise to the discharge value of the auxiliary gap, which is approximately 700 volts. Following this the telephone bell magnets, induction coils and hook switches have been damaged. Two years of service with fifty or more of these arresters installed on high voltage lines has shown that this trouble is far from serious, since not more than ten or twelve vacuum gaps have been destroyed each year. On the other hand not a single telephone transformer burn out has occurred, a single operator hurt, or any extensive damage done to the telephone instruments, although the operators have used them at the time of direct strokes of lightning on the line and in one case when a 22,000-volt line fell on the telephone line.

The tests made on the arrester described have included the impressing of full 110,000 volts on the telephone line. This test did not damage the arrester or the telephone instrument and shows that the protection would be complete in case of a cross between the telephone line and the 110,000-volt line. Previous to the installation of these arresters, damage amounting to more than $1,000 was done to telephones and instruments in one year of service. With the complete telephone equipment installed as outlined on the system of the Georgia Railway & Power Company it has been found perfectly safe to continue the high-voltage telephone communication through underground cables to an office telephone or to a telephone switchboard. The load dispatcher, through his telephone board, can communicate directly with all of the water-power stations and substations, although he is located in Atlanta and his board is connected to the high-voltage lines through approximately three miles of standard underground telephone cable. No trouble on this cable of any kind has been experienced due to high voltage since the installation of the protection.

VII. Special Protection Schemes

Use of Rheostat in Grounded Neutral.—The system of connections shown in Figs. 180 and 181 is deserving of special mention. To prevent the line switch from opening automatically when a ground occurs on the line, the scheme shown in Fig. 180 is adopted. It consists of a series transformer in the earth connections of the grounded rheostat, the secondary of which is connected to an instantaneous overload circuit-opening type relay, having its contacts inserted in the tripping circuit between the main relays of the line switch and the tripping coil of this line switch. The idea of this scheme is to open the tripping circuit by the instantaneous relays before the inverse time limit relays have closed their contacts. The existence and severity of the ground are indicated by an alarm bell, a signal lamp and an ammeter. This arrangement, therefore, permits the operator to cut out the line in trouble without service interruption in the following way: If a ground occurs, the operator will trip one of the line switches (of a duplicate line), and if the trouble should be on the line controlled by that switch the reverse power relays at the substations will open the line from the other end. If, however, the ground is on the other line (the bell continuing to ring), the operator will then again close the first switch and trip the other, which will close the line in the manner just mentioned without service interruption. For greater reliability the reverse-power relays at substations may be installed in duplicate.

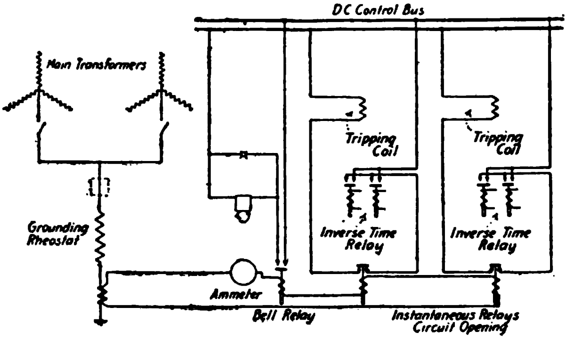


Fig. 180.—System of Connections Between Grounded Rheostat in Neutral and Line Switches

The great difficulty is in making a self-contained rheostat that will withstand the high voltage of a high voltage transmission or cable system and offer at the same time more than one low factor of safety against flashover. A rheostat for this purpose should be built in several separate sections connected in series, each section being placed on high voltage insulators in separate fireproof compartments, of concrete, brick, asbestos, etc. The compartment should permit of building each rheostat section for about one-sixth to one-tenth of the operating voltage, so the factor of safety against flashover and the consequent reliability of the rheostat itself, will be materially increased. With such a rheostat there is very little probability of any oscillatory arcing on account of the method of earthing the system, but if any doubt should exist as to the permanency of its reliability, the system can readily be changed into an insulated one by opening the transformer neutral with the aid of the switch installed in this circuit.

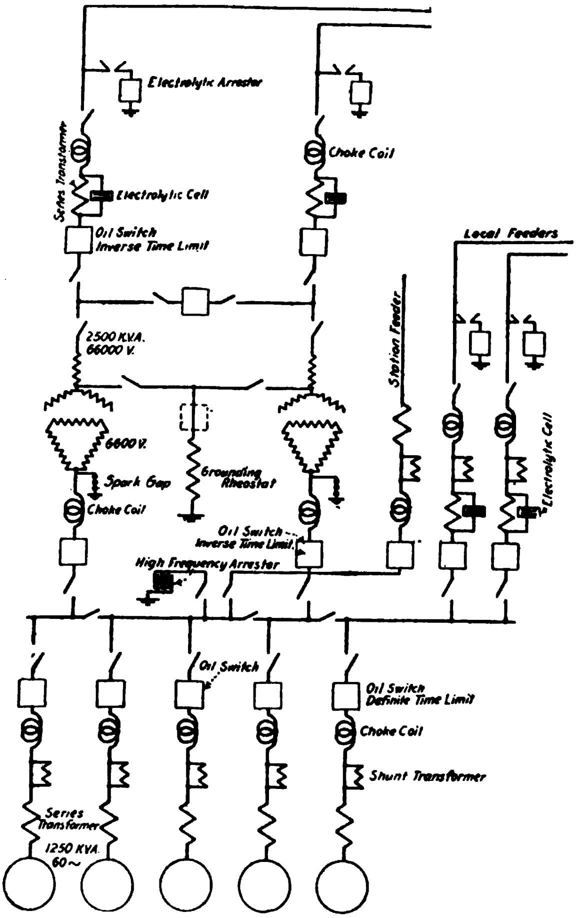


Fig. 181.—System of Connections for 66,000 Volt System Showing Special Use of Rheostat in Grounded Neutral and of an Electrolytic Cell in the Line

In this plant there has also been provided additional protection in the form of choke coils in each circuit connected to the generator bus-bars. The choke coils are wound with Swedish iron so as to obtain high ohmic resistance under high frequency surges entering over the low voltage local feeders. In addition to this protection, and for the same reason, each series transformer on the outgoing 66,000 volt lines is shunted by a small electrolytic cell and a high frequency condenser arrester placed on the low-voltage bus-bars in addition to the usual electrolytic arresters and choke coils on the outgoing transmission lines.

With reference to the value of the earthed rheostat with the above described interconnection between it and the line switches, very reliable service was given even during the construction of the transmission line, which line was originally built with a single three-phase circuit. However, very soon after this first circuit was placed in operation a second circuit was strung on the same towers while in operation at 60,000 volts. By keeping the conductor of the second circuit well earthed the linemen were not endangered and practically uninterrupted service was maintained throughout despite a large number of accidental grounds caused by the second line coming in contact with the live line due to strong winds, etc.

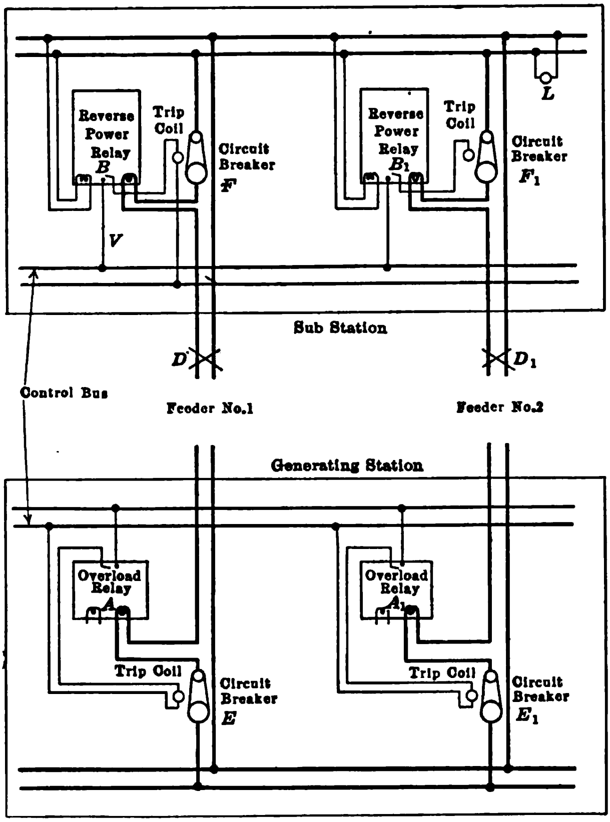


Fig. 182.—Use of Overload and Reverse Power Relays at Generating Station and Sub-station

Relays for Protecting Parallel Feeders.—Selective reverse-power relays for the protection of parallel feeders, which will not operate on overload, are sometimes needed. In Fig. 182 two feeders are shown running from a generating station to a substation. At the generating station plain over-load relays are used set for a comparatively long time element, and at the substation two sets of selective reverse-power relays, one set for each feeder. When the direction of the energy flow is normal, that is, both feeders supplying energy to the substation, the reverse-power relays cannot trip their breakers or switches no matter how heavy the load may be. If a ground or short circuit occurs at *D* on feeder No. 1, there will be a heavy flow of energy through the substation and back on feeder No. 1 to the point of the short circuit. Thus the direction of energy flow is reversed at relay *B* in the substation. This reversal of direction of energy flow is the only thing that can cause relay *B* to operate. As soon as switch *F* is opened, the load on No. 2 feeder falls back to normal, and it continues to operate the substation. If the short circuit continues, the overload relay *A* will trip its switch and the line will then be clear.

Protection of an Automatic Converter.—In case of a short circuit (Fig. 183) on the alternating current system direct current will feed back through the synchronous converter and operate the reverse-current relay opening the solenoid circuit breakers. In case of a local alternating current short circuit the alternating current feeding into the short circuit operates the overload relays and opens the main switch, disconnecting the converter from the line. If both reverse-current relays should fail, the speed-limiting device and the overload coil are both available to open the circuit breakers.

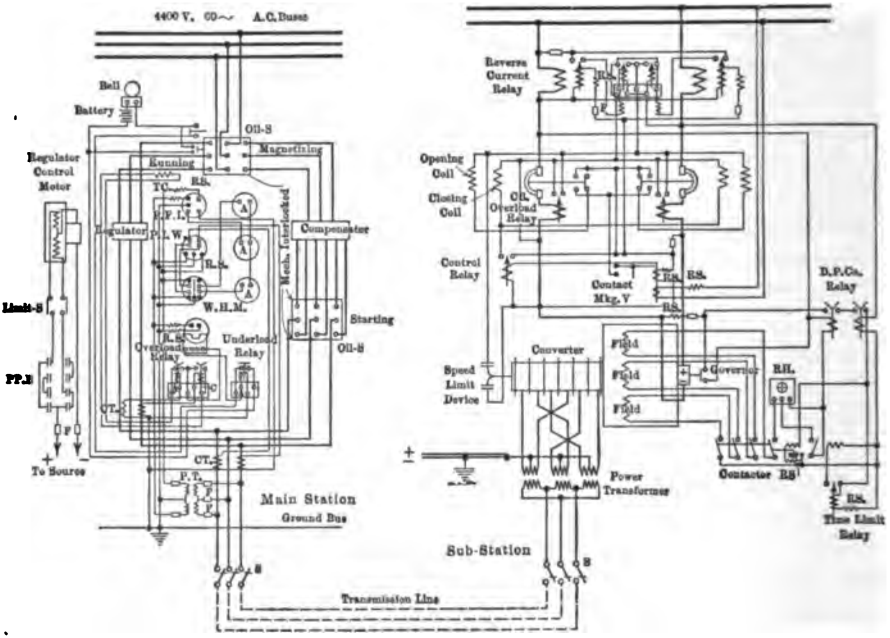


Fig. 183.—System of Connections for Rotary Converter and Control Apparatus

The shut down of the converter from any cause is indicated by the underload relay. For normal stoppage of the synchronous converter, the running switch of the alterating current supply is opened, which leaves the converter running as a direct current motor. The reverse-current relays are set so that they will operate on the current which the converter takes as a direct current motor and their operation opens the main circuit breakers and disconnects the converter from the direct current busbars. As the converter slows down, the governor assumes its starting position and the field contactors open so that everything is ready for a new start. In addition to the governors for closing the field circuit, the converter is equipped with the usual centrifugal speed-limit device.

Protection for Transformer Groups in Parallel.—The reverse-power relay

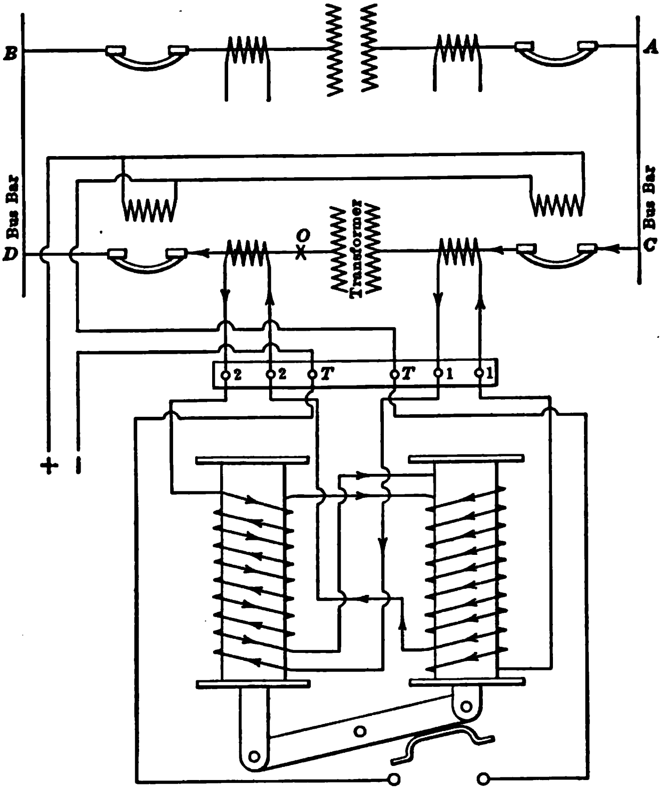


Fig. 184.—Scheme of Connections for Transformer Group

is also suitable for transformer protection where transformer groups are operated in parallel. It is for service where it is desired to open the alternating current circuits when the direction of energy flow or power is reversed. A circuit breaker with shunt trip coils is required, the relay making connections to the trip coil to open the breaker, the specific purpose being to cut out instantly the faulty group of transformers without otherwise disturbing the system. This relay will operate equally well on delta-delta, delta-star, star-delta or star-star, transformer connections.

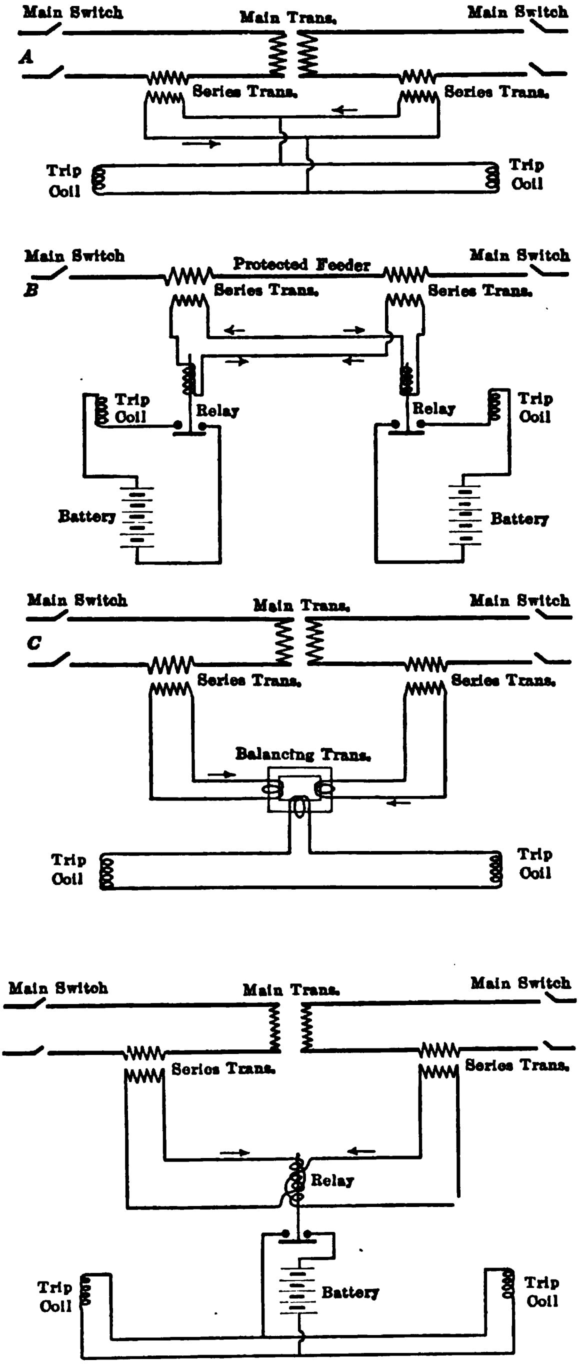


Fig. 185.—The Merz-Price System of Protection Using Pilot Wires

The relay consists of two powerful electromagnets which either close or maintain the tripping circuit open. Upon a reversal of power the relay is adjusted to operate and permit the tripping circuit to be. closed, resulting in a simultaneous opening of the circuit breakers on both the primary and the secondary sides of the transformer group. The diagram of Fig. 184 illustrates the electric circuits of the relay. Instead of tripping the breakers mechanically, it closes a contact which allows current to pass through the shunt trip coils of the breakers, thus permitting them to open. Its operation is independent of overloads or short circuits, series transformer characteristics, potential or direction of energy flow, and operates only when there is a relative reversal of power in the primary and secondary circuits of the transformers.

Assuming the direction of current to be as indicated by the arrows in the diagram, under normal load conditions, the current from *C* to *D* has no effect upon the relay except to keep the contacts of the shunt trip circuits open. Should a fault occur, however, at the point *O*, for instance, the tendency would be for the energy to flow in the direction *A*, *B*, *D*, and *O*, causing a reversal of power in a section of the feeder *D* and *O*. This action likewise produces a reversal of power in the series transformer and causes the relay to operate and close the shunt trip coils of the circuit breakers. Since the circuit breakers both open simultaneously the faulty group of transformers is completely isolated, and the continuity of the system is not interrupted.

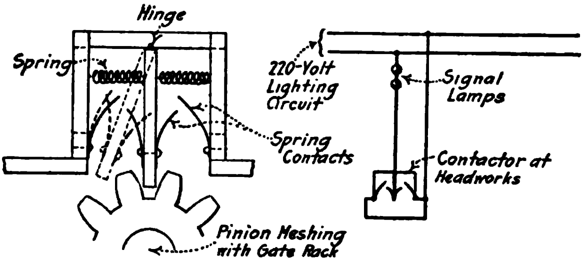
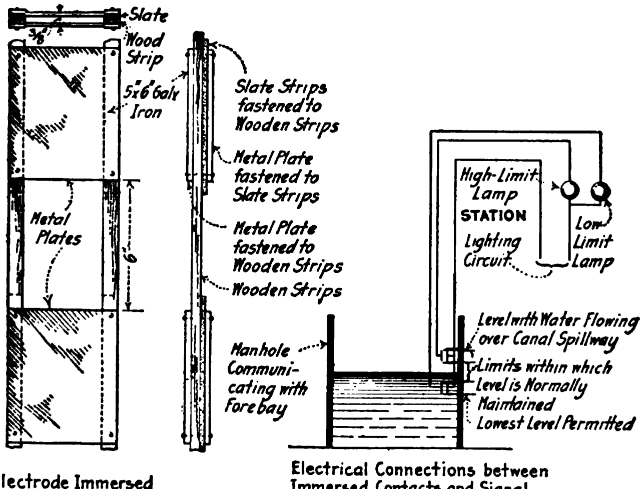


Fig. 186.—Construction and Electrical Connections of Head-Gate Movement Indicator

Forebay Water Level Indicator.—At the Falls Village (Conn.) hydroelectric plant of the Connecticut Power Company the crest of the canal between the pond and forebay is 9 ft. below the pond level. In order


Slate
3/8"
Wood Strip
5x6 Galv Iron
Metal Plates
6"
Slate Strips fastened to Wooden Strips
Metal Plate fastened to Slate Strips
Metal Plate fastened to Wooden Strips
Wooden Strips
Manhole Communicating with Forebay
High-Limit Lamp
STATION
Lighting Circuit
Low Limit Lamp
Level with Water Flowing over Canal Spillway
Limits within which Level is Normally Maintained
Lowest Level Permitted

Electrode Immersed in Forebay

Electrical Connections between Immersed Contacts and Signal Lamps

Fig. 187.—Arrangement of Electrodes in Forebay by Indicate Level by Signals

carefully to regulate the openings of the headworks gates with fluctuations in turbine loads so that no water is wasted over the canal spillway, ingenious signaling devices are used. One arrangement shown in Fig. 186 indicates the amount the headgates are moved and the other shown in Fig. 187 whether the canal level is too low or high.

As shown in Fig. 186 the gate-movement indicator consists of a pivoted strip of wood carrying two connected spring contacts and held in a perpendicular position by springs. The lower end of this wooden strip engages with one of the pinions meshing with the gate rack. Attached to a wooden frame on each side of the pivoted lever are other spring contacts which are connected together electrically. These are joined with one terminal of a lamp in the generating station down stream, the other lamp terminal being connected with the lighting circuit. The movable contact on the gate-movement indicator is connected with the other conductor of the lighting circuit. Thus when the gate is raised or lowered, which is done by means of remote controlled induction motors, the movable contact makes connection with one or the other stationary contact and lights the signal lamp at the station as many times as there are teeth that pass the lever. Since the pitch of the gate rack is about 2 in., it is simple to determine the movement of the gates by multiplying the number of times the lamp lights by two. In making up the records, the amount the gates are raised or lowered is added to or subtracted from the previous gate-opening reading. From previous records of total turbine load pond elevation and gate opening the operator is able to judge how much the gates should be moved.

In order that the operator will be warned automatically when more water has to be supplied to the canal to maintain a certain forebay level, and also when the gates have to be adjusted to prevent water wasting over the canal spillway, contacts are arranged as shown in Fig. 187 in the forebay. They consist of two pairs of iron plates clamped between wooden strips and installed in the forebay so the lower edges of the lower plates are at the lowest elevation at which the forebay should be maintained. The upper edges of the upper plates are at the maximum elevation that the forebay can be maintained at without wasting water over the spillway. Between each pair of plates are insulating separators that hold the plates about 0.375 in. apart. One plate of each set is connected with one side of the signal-lamp circuit, while the other two plates are connected with two signal lamps. The remaining lamp terminals are joined to the other side of the circuit.

Thus when the forebay level is correct the lower plates in the forebay are completely immersed so that the lower-limit signal lamp burns brightly. If not enough water is being supplied to the canal the forebay level drops, causing the lower-limit lamp to dim or even go out, which is a signal that the canal intake gates have to be opened. The amount which they shall be opened is based upon previous records for similar loads. If the load becomes so light that the forebay level rises then the upper-limit lamp begins to glow, getting brighter as the canal level approaches the point where the water will pass over the canal spillway. While this scheme is employed on a system where the conditions are different from those on most systems, this signaling method is applicable most anywhere.

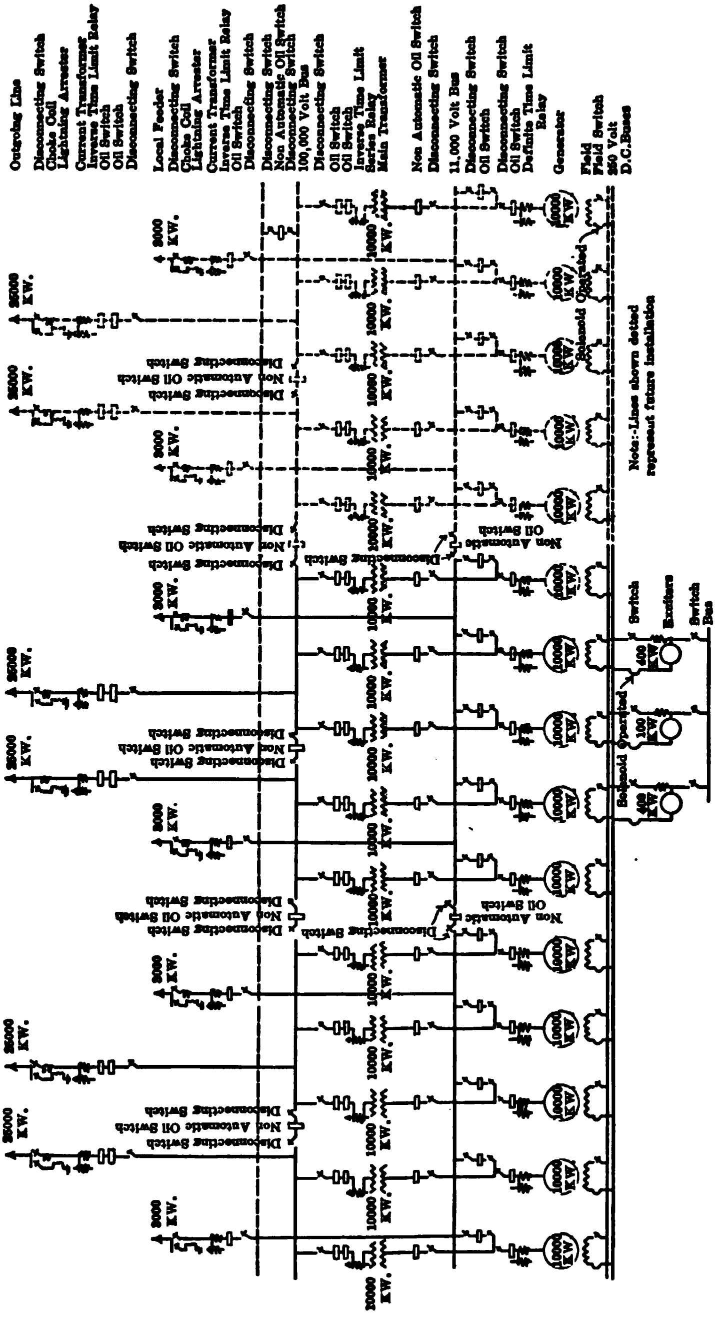


Fig. 188.—A Complete System of Protection for a Large Generating Station Using Series Transformers and Relays

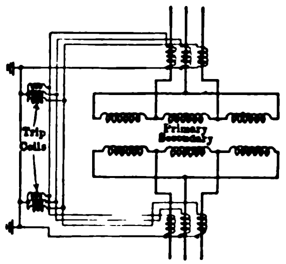


Fig. 189

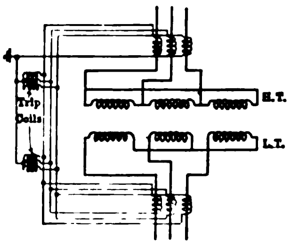


Fig. 190

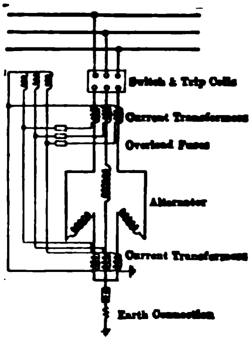


Fig. 191

Figs. 189, 190, 191.—The Ordinary Method of Protection by Means of Series Transformers and Trip-Coils in Connecton with Switches

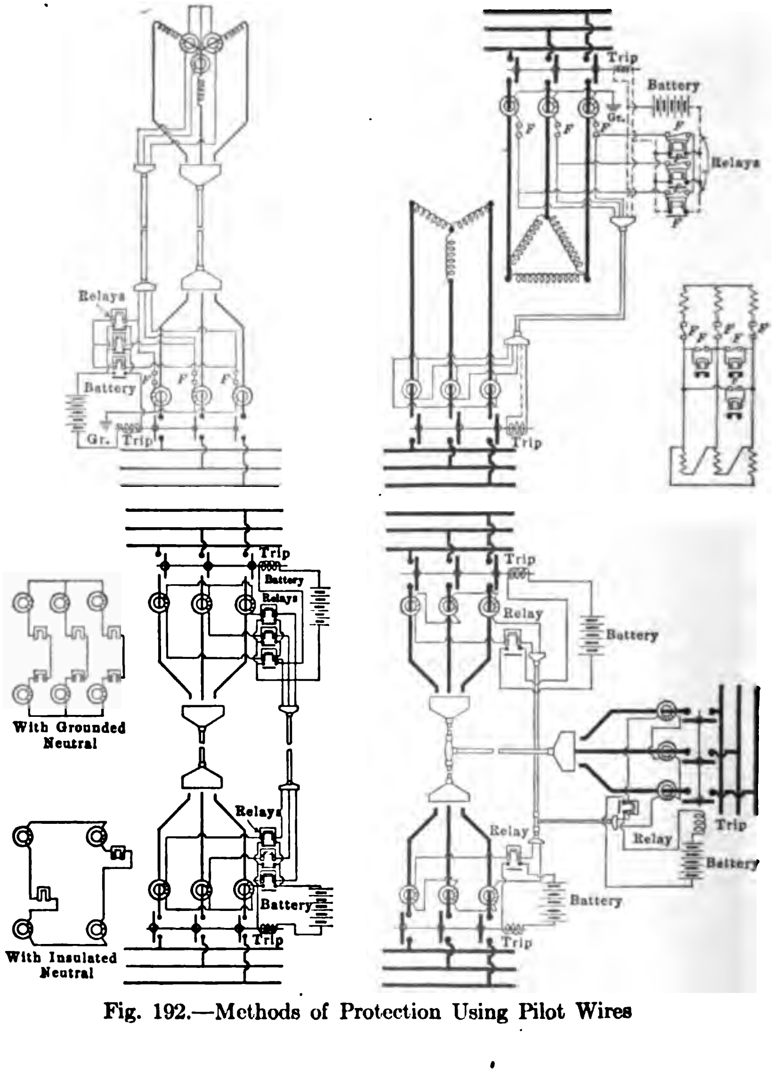


Fig. 192.—Methods of Protection Using Pilot Wires

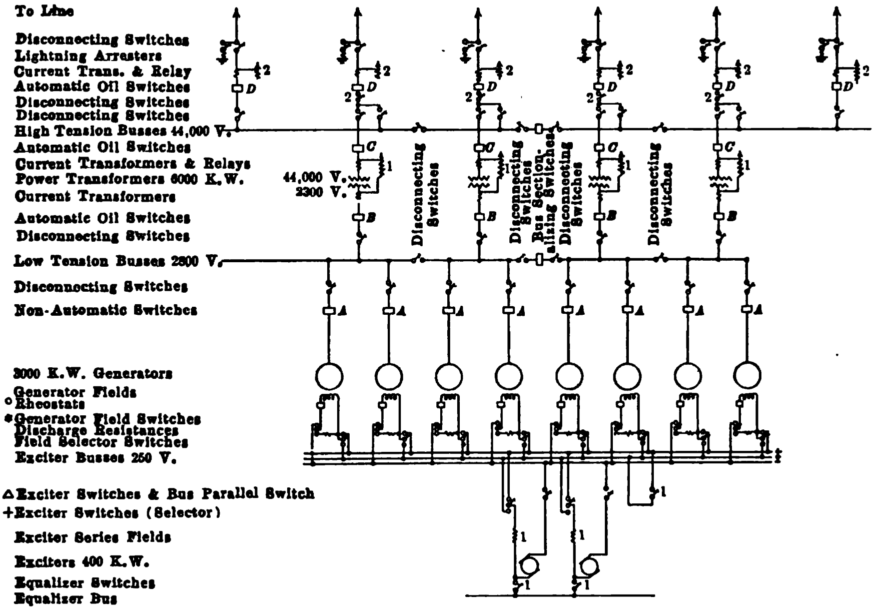


Fig. 193.—Complete System of Connections Showing Method of Protection by Means of Series Transformers and Relays

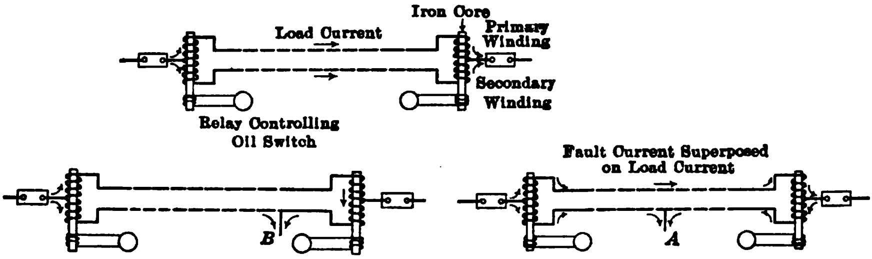

Iron Core
Load Current
Primary Winding
Secondary Winding
Relay Controlling Oil Switch
Fault Current Superposed on Load Current
B
A

Fig. 194.—Split-Phase System of Protection

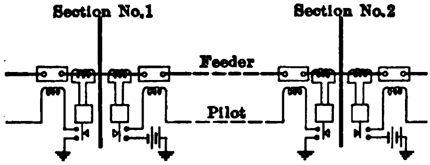


Fig. 195.—Method for Protecting Feeders by Relays and Pilot Wire

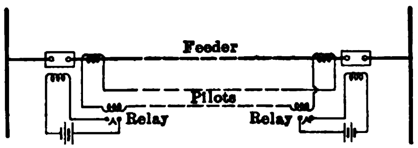


Fig. 196.—Balanced-Voltage System of Protection

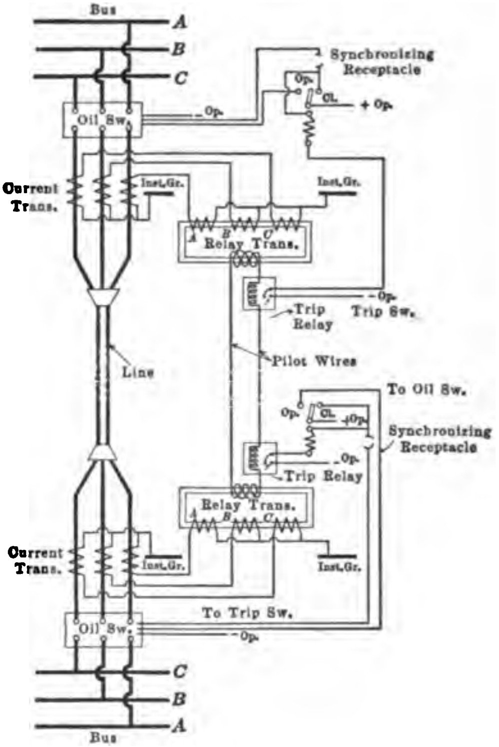


Fig. 197.—A Special Means of Protection Used on a Large System Operating Large Units

CHAPTER VIII

DATA, REFERENCE TABLES AND SYSTEM DIAGRAMS

I. CALCULATION OF SAG AND STRESS IN CONDUCTORS

Formula and Tables for Calculation of Stress and Sag in Conductors.—The following simple method of calculating stress and sag from the forces acting on transmission line conductors as developed by E. V. Pannell (*London Electrical Review*, May 10, 1912) will be found useful. The calculations are based upon the recommendations of the British Board of Trade for overhead line construction but can readily be converted to other standards when necessary. The design conditions considered call for a stress in the conductor not exceeding one-fifth of the ultimate tensile strength at a temperature of 22 deg. Fahr. and a horizontal wind pressure of 30 lb. per sq. ft. (corresponding to 18 lb. per sq. ft. on the projected surface of the wire). These values together with the physical constants of Table 53, are substituted in standard equations for deflection and stress. The physical constants of the above mentioned table differ in some respects from those of another table given elsewhere in this book. Where it seems advisable to use other physical constants for the basis of the accompanying tables and curves, the proper correction factors can be introduced in the method explained which is the fundamental consideration.

Deflection at mid-span, $\delta = (Wl^2) \div (8aS)$

Where W is the loading per foot run in lb.; l is the span in ft.; a the cross section of the conductor in sq. in.; S is the maximum working stress in lb. per sq. in. The loading on the wire (W) is the resultant of its weight w and the wind pressure p, thus,

$$W = \sqrt{w^2 + p^2},$$

and the inclination of the plane in which the conductor will hang is given by,

Angle with vertical, $\theta = tan^{-1} p \div w.$

The two forces w and p act at right angles.

The loading (W) is shown by the curves in Fig. 198, which are plotted from the figures set out in Table 54, and in which both of the components and the resultant have been plotted as a function of the cable diameter. The enormous preponderance of wind over weight loading in the smaller sizes will be noted. This, however, only represents abnormal conditions, inasmuch as the specified pressure of 30 lb. per sq. ft. is only realized under extraordinarily tempestuous circumstances.

TABLE 53.—PROPERTIES OF COPPER AND ALUMINUM STRANDED OVERHEAD CONDUCTORS

	COPPER	ALUMINUM
Relative conductivity, per cent.	100	60
Specific gravity	8.95	2.71
Relative weights for equal conductance	100	50
Relative cross-section	100	166
Tensile strength, lb. per sq. in.	60,000	30,000
Factor of safety	5	5
Maximum working stress	12,000	6,000
Modulus of elasticity	12,000,000	9,000,000
Specific extension λ	.00000008	.00000011
Coefficient of expansion a	.0000093	.0000130
$\beta = a/\lambda$	116	118
Extension in ft. for full working stress, 100 ft. span	.096	.066
Do. 200-ft. span	.192	.132
Do. 400-ft. span	.384	.264

TABLE 54.—PARTICULARS OF STRANDED OVERHEAD CONDUCTORS

DIA. OF CABLE, IN.	EFFECTIVE CROSS-SECTION, SQ. IN.	WEIGHT PER FT., LB.	WIND PRESSURE PER FT., LB.	RESULTANT FORCE PER FT., LB.
		COPPER		
0.40	0.10	0.40	0.60	0.72
0.60	0.22	0.81	0.90	1.21
0.80	0.38	1.43	1.20	1.80
1.00	0.60	2.24	1.50	2.70
1.20	0.84	3.34	1.80	3.90
1.40	1.15	4.65	2.10	6.00
		ALUMINUM		
0.40	0.10	0.12	0.60	0.62
0.60	0.22	0.26	0.90	1.00
0.80	0.38	0.44	1.20	1.30
1.00	0.60	0.69	1.50	1.65
1.20	0.84	1.01	1.80	2.05
1.40	1.15	1.40	2.10	2.50

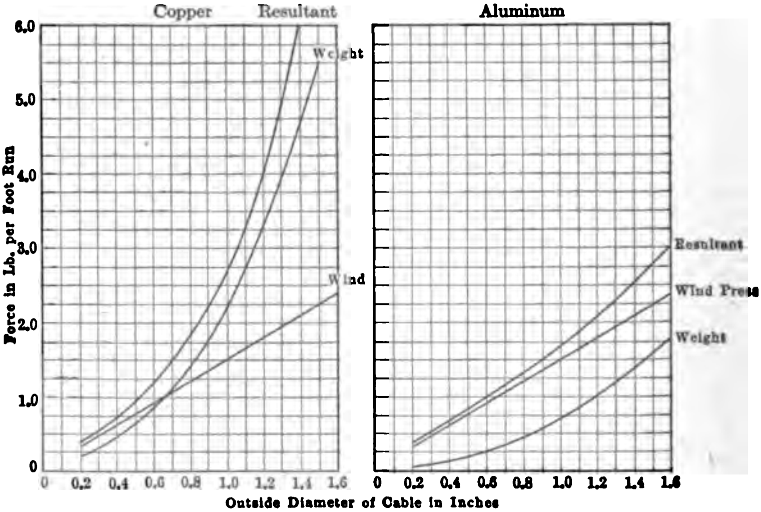


Fig. 198.—Loading Due to Weight and Wind-Pressure on Overhead Conductors

As already stated, the formula given above represents the conditions obtaining at a minimum temperature of 22 deg. F. With increase of temperature the factor of linear expansion will come into play and the deflection will increase. It is highly important to know the value of the maximum deflection under conditions of high summer temperature, in order that the minimum distance of the line above ground-level may be observed and the height of the poles chosen in accordance with the same.

Considering therefore the effect of a rise in temperature $=t°$ F., if $\alpha=$ expansion coefficient and $L=$ total length of conductor, the expansion for a rise of $t° = l\alpha t$, and total length, $L=l+l\alpha t$.

Now, from the properties of the catenary—

$$L=l+8\delta^2/3l \text{ and } L_1=l+8\delta_1^2/3l$$
$$(L_1-L)=8(\delta_1^2-\delta^2)/3l,$$

but $L_1-L=$ extension for temperature rise $t° = l\alpha t$, hence—

$$l\alpha t=8(\delta_1^2-\delta^2)/3l \text{ and } t=8(\delta_1^2-\delta^2)/3l^2\alpha.$$

It has been thought desirable to manipulate the temperature-deflection equation in the above form in order that a correction for the elastic stretch of the wire may be more readily made. It will readily be seen that as the cable expands with increased temperature the stress is relieved. This reduction of stress, however, gives a diminution of strain, and the conductor will, therefore, extend, due to temperature rise, by an amount which is *less* than that calculated by the shortening due to reduction of stress. From the other standpoint it will be seen that the temperature rise for a given deflection will be *greater* than that worked out from the above formula. The correction may, therefore, most conveniently take the form of an increment to the calculated temperature rise. The correction used is a modification of that suggested by Shields in the discussion on a paper by Burne on "Overhead Constructions" (*Journal* I. E. E. (British), Vol. XXXI., p. 432).

This correction may be made as follows: $\alpha=$ per cent. extension per ° F. $\lambda=$ per cent. extension per lb. per sq. in. stress. $\beta=\alpha/\lambda$.

Now for a change in deflection $=\delta'-\delta$, there is a change in stress $=S_1-S$, and $S_1=S\ \delta/\delta_1$; hence the increment for correcting the above temperature $=(S_1-S)/\beta$, and this should be added to the right-hand side of the equation.

On this basis the curves in Fig. 199 have been plotted and the results tabulated. It will be noted that maximum wind pressure is assumed throughout, hence the deflection is not only considerably above the normal value, but the conductor will be swung out of the perpendicular by a considerable angle. As already shown, the value of this angle is $\tan^{-1} p/w$. It is, therefore, unaffected by temperature, and only depends upon the wind pressure and the weight of the wire. Fig. 200 shows this feature graphically, the values of deflection for a 400-ft. span, at 22° F. and the maximum wind pressure, being plotted in polar coordinates.

From the curves in Figs. 199 and 200 will be seen, as might be expected, the relatively greater deflections on aluminum conductors, and the greater effect of a given wind pressure. It should be noted, however, that this is largely due to the abnormal value assumed for the latter quantity. More-over, as will be seen later, a deflection double that of a copper conductor need only call for a pole 10 per cent. higher. The fact that the greater factor in the loading on aluminum cables is this assumed wind pressure, is an advantage on the side of conductors of this material. Under normal circumstances, with moderate winds, the weight of the cable is the more potent factor of the loading, and this value being 50 per cent. lower for the

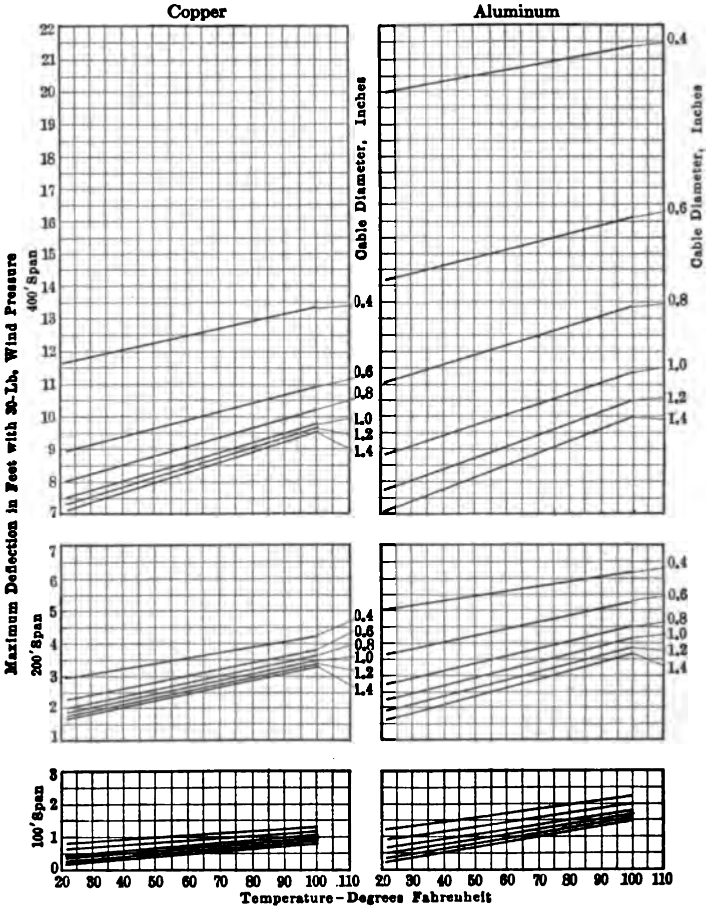


Fig. 199.—Deflections on Overhead Conductors Under Varying Conditions of Temperature

aluminum cables, it follows that the *average* stress in such will be lower in value. This is by no means an unimportant point, as the lower the average stress on any section, the less is the liability to fatigue.

In predetermining the forces acting on the conductors at the lower temperature limit of 22° F. it is necessary to take into account the wind pressure. In calculating the maximum deflection due to the highest summer temperature, however, wind pressure must be eliminated. Apart from the physical impossibility of a hurricane blowing at 100° F., it is necessary to calculate the maximum deflection in a vertical direction in order to estimate the necessary height of the pole or other supporting structure; in other words, the deflection in still air is what is required. Some manipulation is necessary to allow for this change in the conditions, and the author has found it convenient to use a graphic method for effecting this.

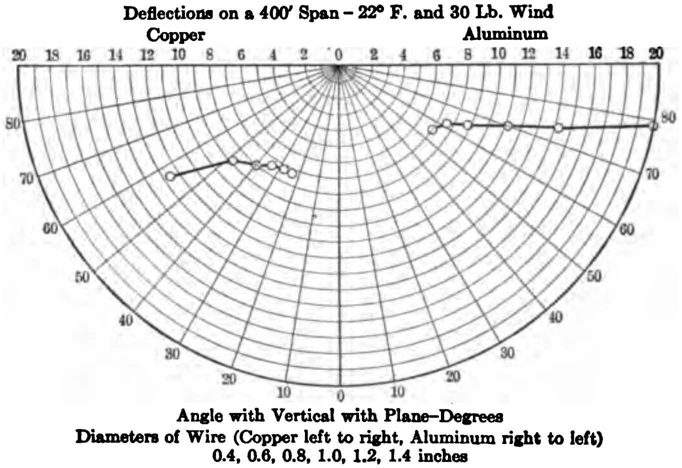


Fig. 200.—Polar Diagram Showing the Angle by which Conductors are Blown Out of the Vertical

The conditions obtaining at 22° F., as has been seen, are expressed by—

$$\delta = Wl^2/8aS.$$

It will be noticed that all save δ and S are constant; hence—

$$\delta = K/S, \text{ and } \delta S = K.$$

If, now, the wind pressure disappears, the state of affairs is given by—

$$\delta_1 = Wl^2/8aS_1, \textit{ i.e.}, \ \delta = K_1/S_1.$$

Ample information is available for the estimating of K and K_1; the latter being obtained, a *locus* is fixed for $\delta_1 = K_1 S_1$. This curve plotted for a 200-ft. span in aluminium is shown in Fig. 201, while at the top of the diagram is the elastic extension curve plotted downwards to represent a contraction. This is obtained simply by multiplying the stress by the elastic constant and by the length of span. The variation of deflection with extension of the cable is calculated from the equation already given—

$$L = l + 8\delta^2/3l,$$

hence a series of deflection curves can be plotted from the values in the elastic extension curve. The points where these lines intersect the δ_1 S_1 hyperbola show the positions where the catenary and elastic laws coincide and give the actual deflections which the conductor will take up, with the corresponding stresses.

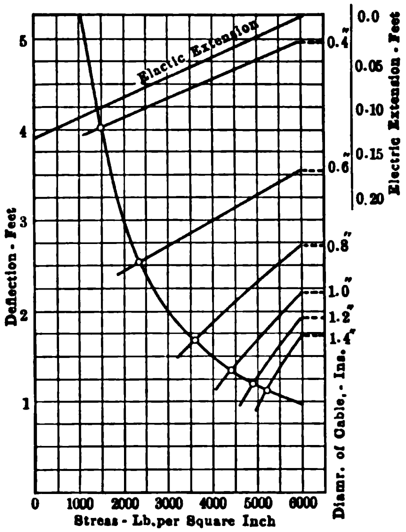


Fig. 201.—Graphical Method for Determining the Reduced Deflection with a Reduction of Stress—Aluminum Cables with 200 Ft. Span

A computation such as this, although somewhat laborious, is the only means of predetermining the actual conditions obtaining when an elastic conductor is used for aerial work. The accuracy of the method depends wholly upon the values chosen for elasticity, and there is room for a considerable amount of experimental work in this connection. Very little

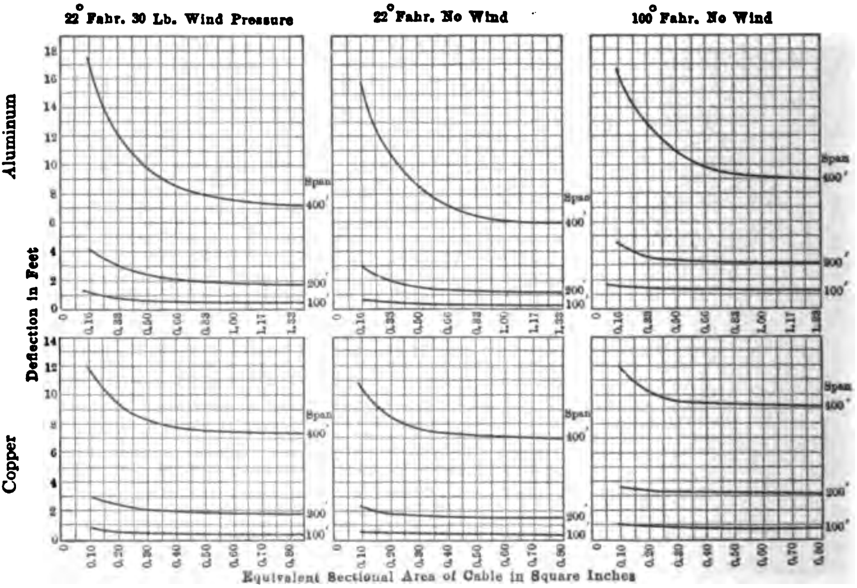


Fig. 202.—Diagrams Showing Comparative Deflections on Copper and Aluminum Overhead Conductors

reliable information is available respecting the physical properties of stranded cables, and with the broadening of the field of electric power transmission such data must be extended.

The respective deflections on the copper and aluminum cables with and without wind-pressure are shown in Fig. 202. These curves, summarize all the foregoing calculations, and it will be seen that they are plotted to a base representing equivalent sectional area which, of course, is a function of current-carrying capacity. Thus the two materials are compared on the fairest possible basis.

Analysis of these results is very instructive—it being seen that the maximum amount by which the deflection on an aluminum line exceeds that for copper is about 35 per cent. With smaller sizes of cable than 0.1 sq. in. of course this ratio will increase, but this illustrates the fallacy of the statement frequently made to the effect that aluminum is only suitable for small and unimportant transmission schemes. It is exactly for the large power layouts that the advantages are best shown, and the greater the amount of power transmitted the better become both the technical and economic features of aluminum. The only point open to question is, at what section of cable does aluminum become superior to copper? The present investigation is carried down to a section of approximately $\frac{1}{10}$ sq. in., or 100 amperes carrying capacity in copper, and it does not seem that any preponderating disadvantage accrues from the replacement of copper by aluminum. If, however, the matter were carried further, down to very small cross-sections, then the large deflections necessary owing to allowance for wind pressure would cause trouble in spacing the conductors.

II. Outdoor Bus Structure Design

Busbar Materials.—In designing outdoor substations and switching stations structural as well as electrical characteristics of different busbar materials must be known so that the structure can be built at a minimum cost consistent with the service it is expected to give. If consideration be given in design only to conductivity and the structural strength is allowed to come to what it will, many times the expense of supporting the busbars will amount to more than it should. Busbar design, therefore, involves a balancing of the cost of busbar material against the cost of supporting and installing it, so that the combined expense will be a minimum. While copper is the material of which busbars are usually constructed, it is not the only material that can be used and straps are not the only shapes which should be installed. Under some conditions aluminum, brass, or even iron or steel, may be desirable, and tubing is often preferable with high voltages because the skin effect is not so noticeable.

Results[1] of investigations of busbar material and dimensions made by

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[1] *Electrical World*, Jan. 8, 1916, pages 86 to 88.

C. A. Mees, formerly designing engineer of Southern Power Company, for outdoor stations are given in the accompanying data. The structural characteristics of different sizes and kinds of pipe and the formulae should assist in the design of pipe framework such as is commonly employed in transmission-line switching stations and other outdoor structures.

Size of Tubing Required.—To show how the accompanying data may be utilized in ascertaining the relative values of different busbar materials, a specific case has been worked out. It is assumed that a busbar *B* in the accompanying diagram (Fig. 203) supports two cross-busbars A_1 and A_2 at the points indicated and that each must carry 1650 amp. The distance between the supports of busbar *B* is 153 in., and the length of both cross-busbars is 15 ft. One-half of each cross-busbar must therefore be supported by busbar *B*. The busbar materials which will be considered are indicated in the first column of Table 67. In the fifth column are the tensile strengths taken from Table 55, giving a factor of safety of five. The permissible current densities, taken from Table 56, are in the next to the last column.

Table 55.—Properties for Busbar Materials

Material	Tensile Strength (Lb./Sq. In.)		Weight (Lb.)		Relative Conductivity (Per Cent).
	Ultimate	Working†	Cu. Ft.	Cu. In.	
Copper, hard drawn	50,000	10,000	555	0.321	100
Copper, annealed	25,000	5,000	550	0.318	103
Aluminum, 99.5 per cent. pure	25,000	5,000	168	0.0975	62
*Brass, rolled	45,000	9,000	530	0.307	60
Iron wrought	55,000	11,000	480	0.278	14.5
Steel, medium	80,000	16,000	490	0.283	. .

* Ordinary rolled brass—60 per cent. copper and 40 per cent. zinc; best brass wire—70 per cent. copper and 30 per cent. zinc. † With factor of safety of 5.

Table 56.—Current Densities That are Satisfactory

Service	Maximum Bus Length (Ft.)	Material	Circ. Mils/Amp.	Amp./Sq. In.
D.C.	Short	Copper bars and tubing	1000	1250
D.C.	Short	Brass tubing and aluminum bars	1600	800
D.C. A.C. lighting	50 75	Copper bars and tubing	1200	1000
D.C. A.C. lighting	50 75	Brass tubing and aluminum bars	2000	650
A.C. inductive	75	Copper bars and tubing	1500	850
A.C. inductive	75	Brass tubing and aluminum bars	2500	500
A.C. inductive	200	Copper bars and tubing	1600	800
A.C. inductive	200	Brass tubing and aluminum bars	2700	475

Starting with this information, the size and cross-section of tubing required, so far as electrical conductivity is concerned, may be determined by referring to Tables 58 to 66. Under the permissible current density look for the total current which must be carried. On the same line to the left the size and cross-sectional area of the tube required are given. The cross-section required for strap material is easily computed by dividing the total current by the permissible current density.

TABLE 57.—CONSTANTS FOR USE IN COMPUTING DEFLECTION

MATERIAL	E	$C = 5/384E$	$C' = 1/48E$
Wrought iron and steel	28,000,000	0.000,000,000,465	0.000,000,000,744
Annealed copper	16,000,000	0.000,000,000,814	0.000,000,001,302
Commercial brass	13,500,000	0.000,000,000,965	0.000,000,001,531
Aluminum (cast bars)	11,500,000	0.000,000,001,132	0.000,000,001,812

TABLE 58.—PERMISSIBLE CURRENT DENSITIES (ORDINARY PRACTICE)

Copper bars: 1000 circ. mils/amp. or 1000 amp./sq. in.
Aluminum bars*: 1000 amp./sq. in. for small sizes
750 amp./sq. in. for general work
500 amp./sq. in. for largest sizes.

* 1.56 times cross-sectional area of copper bars, of same conductivity; therefore greater current densities can be allowed with aluminum bars because of their greater radiating surface.

PHYSICAL AND STRUCTURAL PROPERTIES OF PIPES AND TUBING

TABLE 59.—WROUGHT-IRON AND STEEL STEAM, GAS AND WATER PIPE (STANDARD IRON-PIPE SIZES)

DIAMETER (IN.)			S-IN.^{3}	I-IN.^{4}	r-IN.^{2}	AREA (SQ. IN).	WEIGHT (LB./LIN. FT.)
Nominal	Inside	Outside					
½	0.623	0.840	0.0405	0.0260	0.262	0.2503	0.837
¾	0.824	1.050	0.0704	0.0370	0.334	0.3327	1.115
1	1.048	1.315	0.0959	0.0630	0.420	0.4972	1.668
1¼	1.380	1.660	0.2341	0.1944	0.562	0.6685	2.244
1½	1.611	1.900	0.3248	0.3085	0.623	0.7995	2.678
2	2.067	2.375	0.5996	0.6646	0.787	1.0740	3.609
2½	2.468	2.875	1.0642	1.5298	0.947	1.7120	5.739
3	3.067	3.500	1.7242	3.0174	1.163	2.2380	7.536
3½	3.548	4.000	2.3896	4.7792	1.337	2.6800	9.001
4	4.026	4.500	3.2087	7.2197	1.509	3.1750	10.665
4½	4.508	5.000	4.1555	10.3887	1.681	3.6750	12.340
5	5.045	5.563	5.4770	15.1856	1.880	4.3210	14.501
6	6.065	6.625	8.4086	28.0921	2.245	5.5860	18.762
7	7.023	7.625	12.1785	46.4334	2.590	6.9210	23.271
8	7.982	8.625	16.7674	72.3095	2.948	8.4050	28.177
9	8.937	9.625	22.4312	107.9506	3.283	10.0400	33.701
10	10.019	10.750	29.6158	160.6550	3.673	11.9400	40.065

Physical and Structural Properties of Pipes and Tubing (*Continued*)

Table 60.—Wrought-Iron and Steel Pipe (Double Extra Heavy)

Diameter (In.)			*S*-In.^{3}	*I*-In.^{4}	*r*-In.^{3}	Area (Sq. In.)	Weight (Lb./Lin. Ft.)
Nominal	Inside	Outside					
2	1.491	2.375	1.1089	1.3168	0.705	2.686	9.02
2½	1.755	2.875	2.0055	2.8829	0.842	4.073	13.68
3	2.284	3.500	3.4398	6.0196	1.045	5.524	18.56
3½	2.716	4.000	4.9388	9.8777	1.206	6.772	22.75
4	3.136	4.500	6.8239	15.3539	1.371	8.180	27.48
4½	3.564	5.000	9.0877	22.7192	1.535	9.659	32.53
5	4.063	5.563	12.0708	33.5749	1.722	11.341	38.12
6	4.875	6.625	20.1410	66.7176	2.056	15.807	53.11

Table 61.—Seamless Copper and Brass Tubing (Standard Iron-Pipe Sizes)

Diameter (In.)			*S*-In.^{3}	*I*-In.^{4}	*r*-In.^{3}	Area (Sq. In.)	Weight (Lb./Lin. Ft.)	
Nominal	Inside	Outside					Copper	Brass
½	0.625	0.840	0.0403	0.0169	0.262	0.2474	0.95	0.90
¾	0.822	1.050	0.0708	0.0372	0.333	0.3352	1.31	1.25
1	1.062	1.315	0.1280	0.0842	0.423	0.4723	1.79	1.70
1¼	1.368	1.660	0.2412	0.2005	0.560	0.6944	2.63	2.50
1½	1.600	1.900	0.3342	0.3174	0.620	0.8247	3.15	3.00
2	2.062	2.375	0.5664	0.6732	0.786	1.0907	4.20	4.00
2½	2.500	2.875	0.9976	1.4336	0.950	1.5831	6.04	5.75
3	3.062	3.500	1.7405	3.0456	1.160	2.2572	8.72	8.30
3½	3.500	4.000	2.5955	5.1909	1.330	2.9449	11.45	10.90
4	4.000	4.500	3.3559	7.5491	1.505	3.3380	13.33	12.70
4½	4.500	5.000	4.2128	10.5319	1.700	3.7307	14.60	13.90
5	5.062	5.563	5.2932	14.7278	1.880	4.1808	16.54	15.75
6	6.125	6.625	7.6768	25.4293	2.256	5.0069	19.23	18.31
7	7.062	7.625	11.4789	43.7634	2.598	6.4943	25.53	23.74
8	8.000	8.625	16.3499	70.5092	2.941	8.1607	32.10	29.86

Table 62.—Wrought-Iron, Steel, Copper and Brass Pipe (Extra Heavy)

Diameter (In.)			*S*-In.^{3}	*I*-In.^{4}	*r*-In.^{3}	Area (Sq. In.)	Weight (Lb./Lin. Ft.)		
Nominal	Inside	Outside					W. I. and Steel	Copper	Brass
½	0.542	0.840	0.0480	0.0202	0.250	0.3235	1.09	1.33	1.20
¾	0.736	1.050	0.0861	0.0452	0.321	0.4405	1.39	1.75	1.66
1	0.951	1.315	0.1619	0.1064	0.402	0.6478	2.17	2.48	2.36
1¼	1.272	1.660	0.2940	0.2438	0.523	0.8934	3.00	3.47	3.30
1½	1.494	1.900	0.4152	0.3945	0.604	1.0823	3.63	4.46	4.25
2	1.933	2.375	0.7370	0.8749	0.778	1.4955	5.02	5.73	5.46
2½	2.315	2.875	1.3464	1.9404	0.923	2.2827	7.67	8.72	8.30
3	2.892	3.500	2.2432	3.9255	1.135	3.0523	10.25	11.76	11.20
3½	3.358	4.000	3.1568	6.3136	1.306	3.7097	12.47	14.39	13.70
4	3.818	4.500	4.3026	9.6809	1.475	4.4551	14.97	17.33	16.50
5	4.181	5.563	7.4186	20.6339	1.839	6.1130	20.54	23.94	22.80
6	5.750	6.625	12.3260	40.8297	2.193	8.4960	28.58	33.60	32.00

Note.—Extra-heavy tubing has the same properties as extra-heavy wrought-iron and steel pipe, except as to weights.

TABLES 63 AND 64.—AMPERE CAPACITY OF SEAMLESS TUBING OF STANDARD IRON-PIPE SIZES

SIZE (IN.)	SECT. AREA (CIRC. MILS)	CURRENT DENSITY (CIRC. MILS PER AMP.)							SIZE (IN.)	SECTIONAL AREA (SQ. IN.)	CURRENT DENSITY (AMP. PER SQ. IN.)						
		1000	1200	1500	1600	2000	2500	2700			1250	1000	850	800	650	500	475
½	315,000	315	262	210	197	157	126	117	½	0.2474	309	247	210	198	161	124	117
¾	426,790	427	356	285	267	213	171	158	¾	0.3352	419	335	285	268	218	168	159
1	601,351	601	501	401	376	301	241	223	1	0.4723	590	472	401	378	307	236	224
1¼	884,138	884	737	589	553	442	354	327	1¼	0.6944	868	694	590	555	451	347	330
1½	1,050,041	1,050	875	700	656	525	420	389	1½	0.8247	1,031	825	701	660	536	412	392
2	1,388,723	1,389	1,157	926	868	694	555	514	2	1.0907	1,363	1,091	927	873	709	545	518
2½	2,015,666	2,016	1,680	1,344	1,260	1,008	806	747	2½	1.5831	1,979	1,583	1,346	1,266	1,029	791	752
3	2,873,957	2,874	2,395	1,916	1,796	1,437	1,150	1,064	3	2.2572	2,821	2,257	1,919	1,806	1,467	1,129	1,072
3½	3,749,565	3,750	3,125	2,500	2,343	1,875	1,500	1,389	3½	2.9449	3,681	2,945	2,503	2,356	1,914	1,472	1,399
4	4,250,075	4,250	3,542	2,833	2,656	2,125	1,700	1,574	4	3.3380	4,172	3,338	2,837	2,670	2,170	1,669	1,586
4½	4,750,076	4,750	3,958	3,167	2,969	2,375	1,900	1,759	4½	3.7307	4,663	3,730	3,171	2,985	2,425	1,865	1,772
5	5,323,162	5,323	4,436	3,569	3,327	2,662	2,129	1,972	5	4.1808	5,226	4,181	3,554	3,345	2,718	2,090	1,986
6	6,374,985	6,375	5,312	4,250	3,984	3,187	2,550	2,361	6	5.0069	6,259	5,007	4,256	4,006	3,254	2,503	2,378
7	8,268,802	8,269	6,891	5,513	5,168	4,134	3,308	3,063	7	6.4943	8,118	6,494	5,520	5,195	4,221	3,247	3,085
8	10,390,530	10,390	8,659	6,927	6,494	5,195	4,156	3,811	8	8.1607	10,201	8,161	6,937	6,529	5,304	4,080	3,876

TABLES 65 AND 66.—EXTRA-HEAVY SIZES

½	411,893	412	343	275	257	206	165	153	½	0.3235	404	323	275	259	210	162	154
¾	560,862	561	467	374	350	280	224	208	¾	0.4405	551	440	374	352	286	220	209
1	824,805	825	687	550	515	412	330	305	1	0.6478	810	648	551	518	421	324	308
1¼	1,137,513	1,137	948	758	711	569	455	421	1¼	0.8934	1,117	893	759	715	581	447	424
1½	1,378,028	1,378	1,148	919	861	689	551	510	1½	1.0823	1,353	1,082	920	866	703	541	513
2	1,904,130	1,904	1,587	1,270	1,190	952	762	705	2	1.4955	1,869	1,495	1,271	1,196	972	748	710
2½	2,906,425	2,906	2,422	1,938	1,817	1,453	1,163	1,077	2½	2.2827	2,853	2,283	1,940	1,826	1,484	1,141	1,084
3	3,886,310	3,886	3,239	2,591	2,428	1,943	1,555	1,691	3	3.0523	3,815	3,052	2,594	2,442	1,984	1,526	1,450
3½	4,723,338	4,723	3,936	3,149	2,952	2,362	1,889	1,749	3½	3.7097	4,637	3,710	3,153	2,968	2,411	1,855	1,762
4	5,672,412	5,672	4,727	3,782	3,545	2,836	2,269	2,101	4	4.4551	5,569	4,455	3,787	3,564	2,896	2,228	2,116
5	7,783,316	7,783	6,486	5,189	4,865	3,892	3,113	2,883	5	6.1130	7,641	6,113	5,196	4,890	3,973	3,056	2,904
6	10,817,447	10,817	9,014	7,212	6,761	5,409	4,327	4,006	6	8.4960	10,620	8,496	7,222	6,797	5,522	4,248	4,036

To find the weight per foot of rectangular sections, multiply the cross-section in inches by twelve and by the weight per cubic inch (shown in Table 55). The weight per foot of pipe may be read direct in Tables 59 to 62. By substituting the computed weight in the formula for obtaining the maximum bending moment in a uniformly loaded beam with two symmetrically placed concentrated loads, the following is obtained:

$$M_{max}=\frac{Wt.B\times 153}{8}+\frac{Wt.A\times 55}{2}$$

By inserting M_{max} as computed from this equation and f, as given in Table 55, in the formula $S=M_{max}\div f$, the required section modulus of busbar B is obtained.

To ascertain whether the tube size previously selected for conductivity has the correct section modulus, Tables 59 to 62 are referred to, and the values of S as found there are compared with the required value S as computed. The dimensions chosen for strap material should be such that their product is the cross-section required for conductivity and also such that when they are substituted in the formula $S=(bd^2)\div 6$ (where b is the thickness and d the depth of a strap laid on edge) a value equal to or greater than the required sectional modulus is obtained.

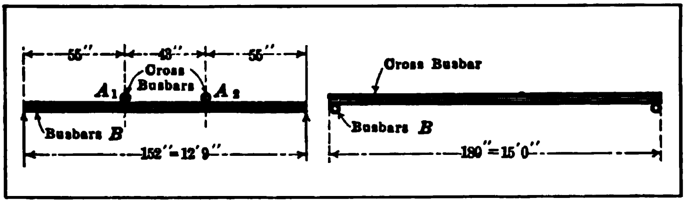


Fig. 203.—Conditions Assumed for Example Showing Application of Data

Deflection of Tubing.—The dimensions required to prevent a deflection of more than 1/360 of the span may also be determined from the tables with the help of the following formulae:

Case 1.—Bar supported at both ends and uniform load.

$$\text{Required } I=\frac{5Wl^3}{384ED}=\frac{CWl^3}{D}.$$

Case 2.—Bar supported at both ends and load concentrated at mid-span.

$$\text{Required } I=\frac{Pl^3}{48ED}+\frac{5W_2l^3}{384ED}=\frac{l^3(C'P+CW_2)}{D}$$

Case 3.—Bar supported at both ends and two symmetrical loads.

$$\text{Required } I=\frac{Pa(3l^2-4a^2)}{24ED}+\frac{5W_2l^3}{384ED}=\frac{C'Pa(6l^2-8a^2)+CW_2l^3}{D}$$

In which a is distance from load to nearest support; W is total load (in pounds) uniformly distributed and including weight of bar; W_2 is total weight of bar (in pounds); *P* is load (in pounds) concentrated; *l* is length of span (in inches), and *D* is deflection (in inches).

The values of *E*, *C* and *C′* are given in Table 57. When *I* is computed, the size of tube needed can be ascertained by using Tables 59 to 62.

TABLE 67.—CURRENT 1650 AMP. (SEE FIG. 203)

METAL	SIZE	WT./LIN. FT.	*M* (in LB.)	*F* (LB./SQ. IN.) FACTOR OF SAFETY, 5	*S* REQUIRED	*S* ACTUAL	CONDUCTIVITY (AMP.)	
							Per Sq. In.	Total
Aluminum	2 in x ¼ in. x 5¼ in.	3.00	2,235	5,000	0.45	2.88	620	1,628
Aluminum	2 in. x 5/16 in. x 4¼ in.	3.04	2,235	5,000	0.45	1.88	620	1,647
Hard copper	2 in. x ¼ in. x 3½ in.	6.74	4,710	10,000	0.47	1.02	1,000	1,750
Soft copper	2 in. x ¼ in. x 3½ in.	6.74	4,710	5,000	0.94	1.02	1,000	1,750
Seamless copper tube	2½ in. std.	6.04	4,375	10,000	0.44	1.00	1,000	1,583
Seamless copper tube	2 in. ex. h.	5.73	4,140	10,000	0.41	0.74	1,000	1,496
Seamless brass tube	3 in. std.	8.30	5,910	9,000	0.66	1.74	600	1,354
Seamless brass tube	2½ ex. h.	8.30	5,910	9,000	0.66	1.35	600	1,370
Seamless brass tube	3½ std.	10.90	7,545	9,000	0.84	2.60	600	1,767
Seamless brass tube	3 in. ex. h.	11.20	7,775	9,000	0.86	2.24	600	1,831

TABLE 68.—USEFUL CROSS-SECTION EQUIVALENTS

1 mil = 0.001 in.
1 circ. mil = 0.7854 sq. mil.
1 sq. mil = 1.273 circ. mil.
1 sq. in. = 1,273,240 circ. mils = 1,000,000 sq. mils.

In the selection of straps for busbars it must be borne in mind that twisting occurs before the safe limits for other phenomena are reached. By experiment the following limitations have been obtained: The unsupported span should not exceed 7 ft. 6 in. for copper and 10 ft. for aluminum. Furthermore, it has been found that these spans should not be attempted without providing rigid clamps over separators at a spacing not exceeding 3 ft. 9 in.

For columns or struts use a maximum ratio of slenderness $l \div r = 120$ and $P = 19{,}000 - (100l) \div r$ up to a maximum value of 13,000 lb. per square inch.

III. USEFUL DIAGRAMS AND DATA

Flow of Water in Open Channels.—The chart of Fig. 204 affords a compact convenient means for solving graphically flow problems based on the well-known Kutter formula. In the notation, *R* is hydraulic radius or mean depth; S is slope of the water surface; n the coefficient of roughness and c the constant in the expression, $V=c\sqrt{RS}$ is taken as,

$$c=\frac{41.6+(0.0028/s)+(1.81/n)}{1+[41.6+(0.0028/s)]\,(n/\sqrt{R})}.$$

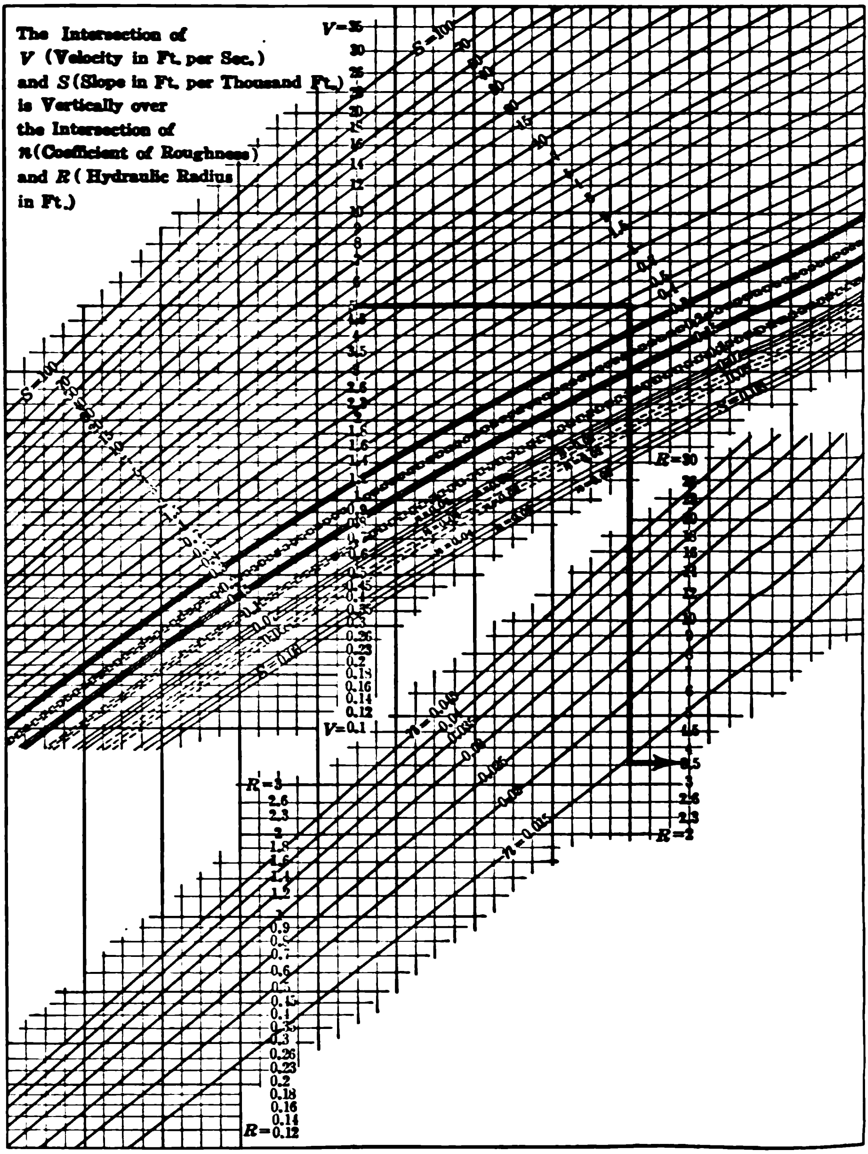
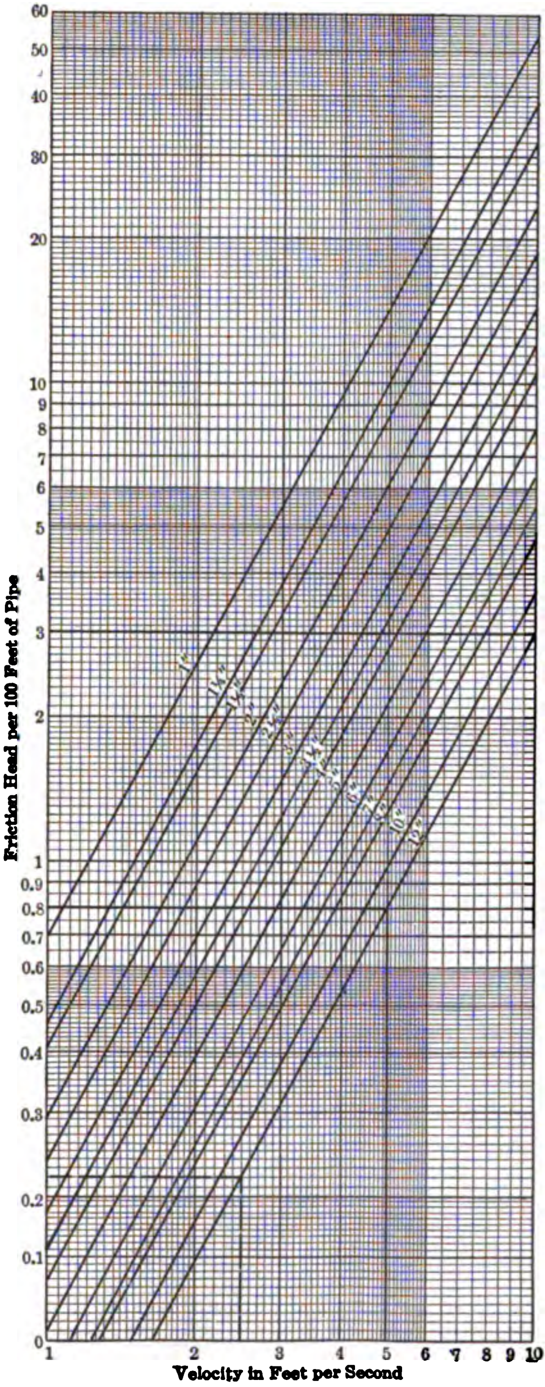


Fig. 204.—K. R. Kennison's Chart for Calculating Flow of Water in Open Channels Based on Kutter's Formula



Friction Head in Pipes 1 to 12 In. in Diameter

Fig. 205.—Chart for the Calculation of Friction Loss in Wrought-Iron Pipes

By means of the diagram any one of the four variables, *V*, *R*, *S*, or *n* can be found when the other three are known.

Friction Loss in Wrought-Iron Pipes.—The curves of Fig. 205 deal with three variables so that in case two are known the third can be found directly. The diagram is plotted with velocities from 1.0 to 10.0 ft. per sec. and friction head per 100 ft. from 0.1 ft. to 100 ft.

Example.—Assume it is desired to know the drop in head per 100 ft. of 12 in. pipe with a velocity of water of 5 ft. per sec. Starting on the lower scale at 5 ft. per sec. and running vertically up to a 12 in. pipe, then horizontally across to the left hand scale, it is found that the drop in head will be 0.8 ft. per 100 ft. of pipe.

Siphons.—When water is lifted by a pipe line to a greater height than the initial water level by siphon action in the course of such a line over valleys and the like, the discharge may be taken equal to that of an ordinary pipe. In such cases, however, special attention must be given to bends and elbows. The head necessary to overcome the friction of bends in the pipe when deducted from the actual head will give the head under which the discharge will take place.

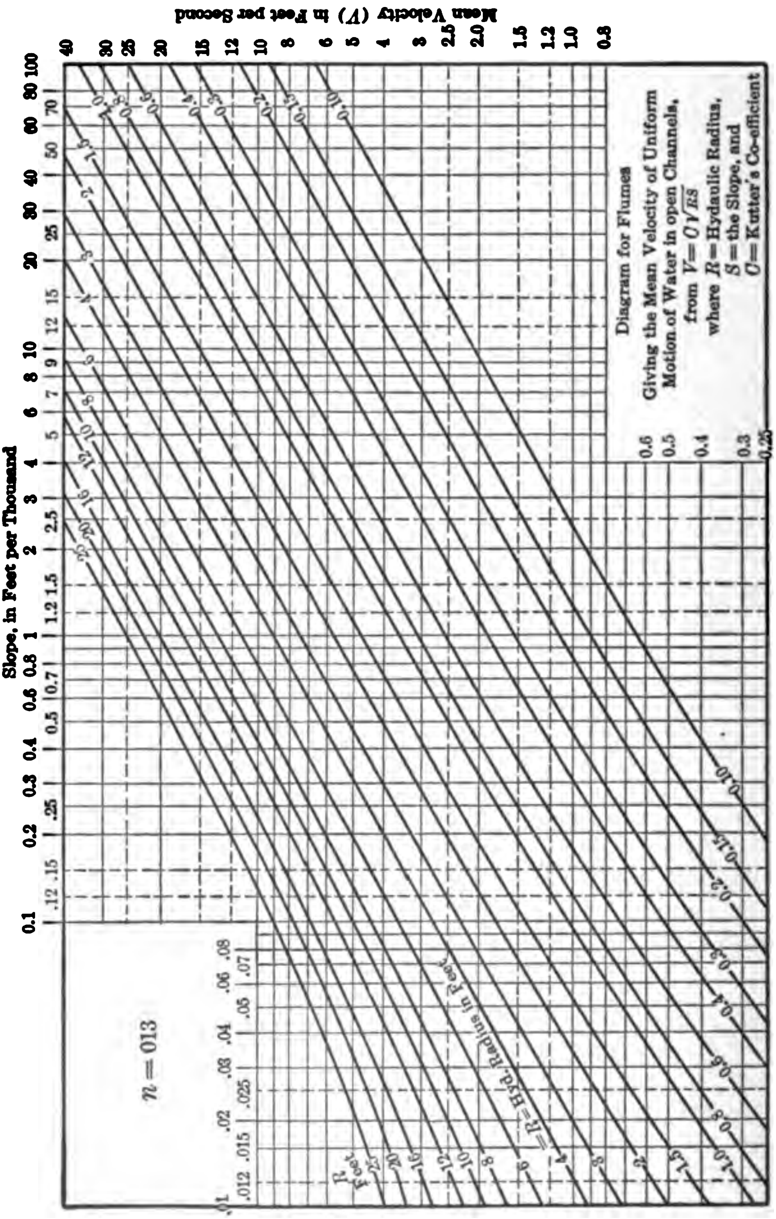


Fig. 206.—Diagram for Flow Calculations in Open Channels

In all siphons, arrangements must be made to secure an effective flush through them.

Specific Speeds for Different Heads and Wheel Ratings.—Present practice indicates that the Francis turbine wheel is suitable for heads as high as 700 ft. and specific speeds (metric units, see page 27) as low as 12, and impulse wheels for heads up to 3000 ft. or over, with specific speeds as high as 4 for heads up to 2000 ft. There are so few plants employing heads above 2000 ft. that practice has not shown just what specific speeds can be reached with impulse wheels under these extra high heads. In Fig. 208 is shown a graphical solution of the general equation for specific speed for heads from 100 to 2500 ft., speeds from 200 to 720 r. p. m. and horse-powers from 1000 to 25,000 as worked out by J. P. Jollyman of the Pacific Gas and Electric Company, San Francisco, Cal. ("Proceedings" June, 1915, Convention National Electric Light Association). An inspection of this diagram shows that there are many combinations of head, speed and output which give specific speeds between 4 and 12 and which cannot therefore be met by either a Francis turbine or by a single jet impulse wheel. To secure a proper solution it becomes necessary to change the speed or the output required from a single jet wheel. In general it may be said that the most desirable speeds for water wheel generators from 3000 kw. to 15,000 kw. are about 400 r. p. m., and that this speed tends to call for impulse wheels having high specific speeds and Francis turbines having low specific speeds.

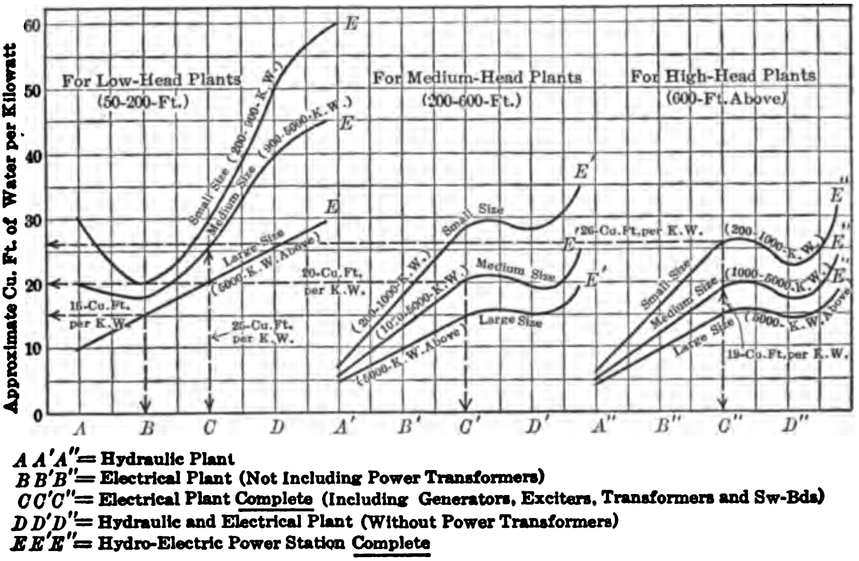
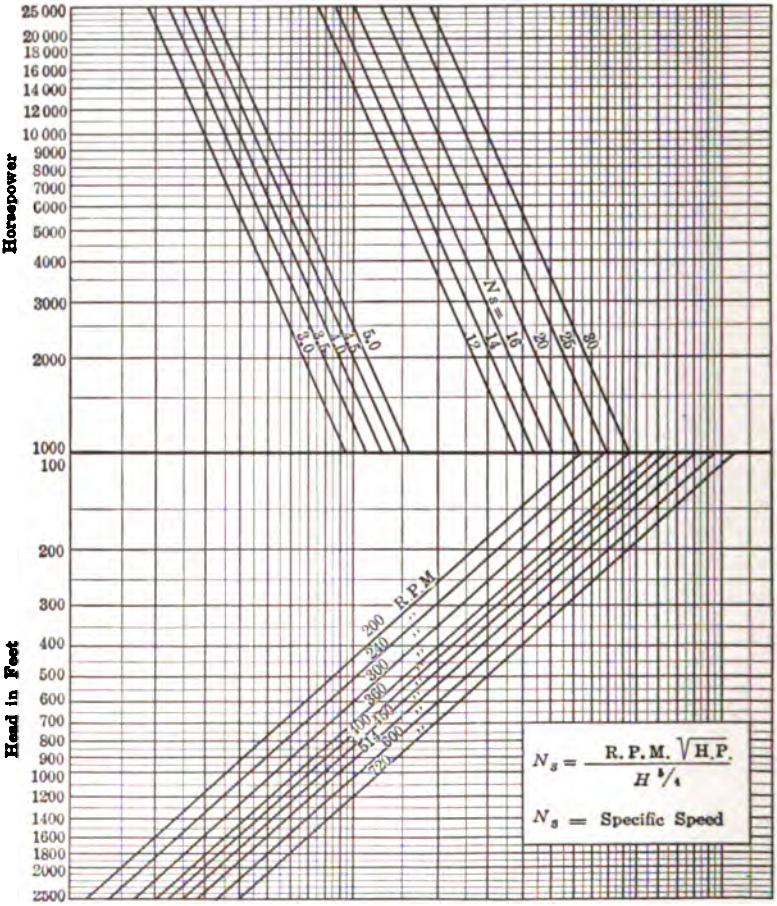


Fig. 207.—Approximate Amounts of Water in Cu. Ft. per Kw. for Low, Medium and High Head Plants of Small, Medium and Large Rating

From the standpoint of efficiency the water wheel is by far the most important part of the plant, since under favorable conditions a greater gain can be secured in the efficiency of the wheel than in any other part. It is therefore essential that the speed and output of the units be selected with reference to securing the best possible conditions for the water wheels.



$$N_s = \frac{\text{R.P.M.}\sqrt{\text{H.P.}}}{H^{5/4}}$$

N_s = Specific Speed

Fig. 208.—Specific Speed Curves for Impulse and Reaction Water Wheels

(See page 27 for derivation of formula)

Minimizing leakage and taking care of end thrust are probably of greatest importance in the design of Francis turbines. Balancing is automatically accomplished by proper arrangement of the leakage ports. If unchecked by a governor, water wheels may attain 200 per cent. of rated speed, therefore generators used with them should be designed to withstand the excessive stresses and the increases of voltage which are caused thereby.

Rating of Governors.—The following formulae can be used to approximate closely the size of governor required for any water wheel having wicket gates, as made by the different governor manufacturers.

$$(1)\ \text{Rating in ft.-lbs.} = \left[\frac{KH}{10}+3\right]D^2N$$

$$(2)\ \text{Rating in ft.-lbs.} = \frac{Hp \times C}{\sqrt{H}}$$

$$(3)\ \text{Rating in ft.-lbs.} = \frac{Hp \times D}{4}$$

Where, Hp is horse-power of the wheel unit; H is operating head; D is diameter of runner in inches; K is ratio of width to diameter of runner; N is number of runners and C is a constant.

Formula (1) may be used for governors made by Platt Iron Works; formula (2) for those made by Allis Chalmers Manufacturing Company, S. Morgan Smith Company, Wellman-Seaver-Morgan Company and the Pelton Water Wheel Company; and formula (3) for those made by James Leffel and Company. The constant C for formula (2) has a value ranging from 20 to 55 depending upon the head, power, type of guide vanes, gates, gate riggings, etc. For a maximum governor effort to open gates of about 8000, the value of C may be considered about 32. Manufacturers should be consulted in selecting the rating for a governor especially when the effort to overcome unbalance of gate may be excessive.

Weights of Prime Movers and Electrical Machinery.—The straight line curves of Figs. 209*a* and *b* give the approximate weights of machinery of modern design. The weights given are total for complete machine. In Fig. 209*b* the abscissas for the alternator curve should be considered as kva./r. p. m. while for induction motors it should be taken as (kw. output/ r. p. m.). On the average electrical apparatus is not as heavy as prime movers for the same kva./r. p. m.

COST DATA ON ELECTRICAL GENERATING UNITS, MOTORS AND PRIME MOVERS *

TABLE 69.—COST OF MACHINES IN DOLLARS

NAME OF MACHINE	COST IN DOLLARS
New direct-current generators and motors	$4{,}500\left(\frac{Kw.}{R.p.m.}\right)^{.06}$
Second-hand direct-current generators and motors	$1{,}800\left(\frac{Kw.}{R.p.m.}\right)^{.06}$
3600-r.p.m. turbo-alternator sets	$33{,}500\left(\frac{Kw.}{R.p.m.}\right)^{.0768}$
1800-r.p.m. turbo-alternator sets	$29{,}500\left(\frac{Kw.}{R.p.m.}\right)^{.0695}$

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* *Electrical World*, Oct. 2, 1915.—"Cost per Pound of Electrical Machinery," by Leonard A. Doggett.

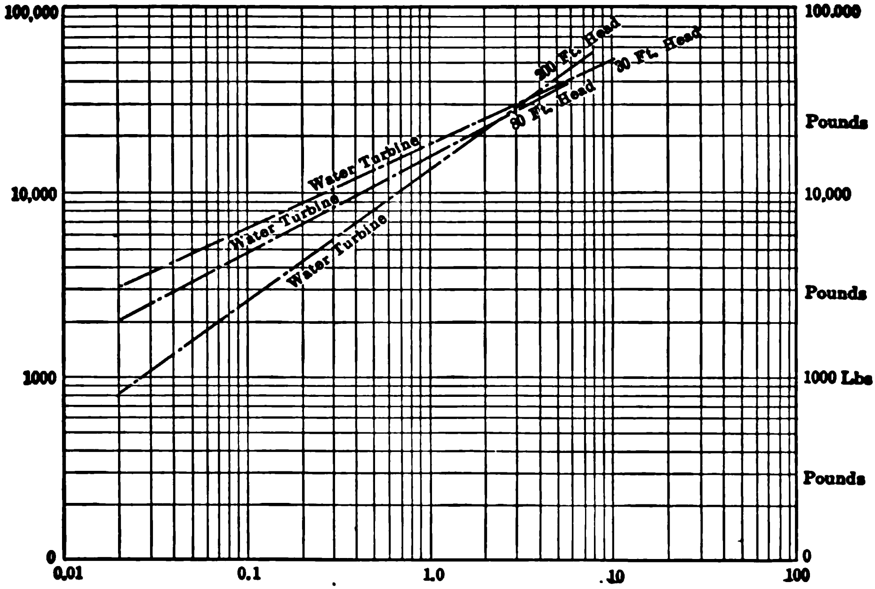


Fig. 209a.—Approximate Weight of Water Turbines

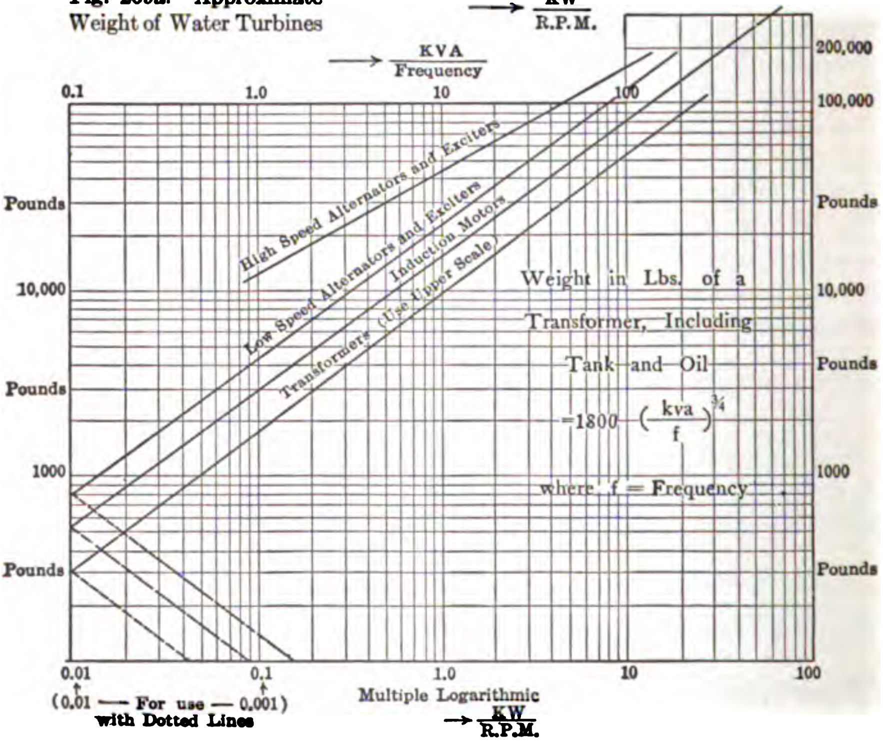


Fig. 209b.—Approximate Weight of Electrical Machinery and Apparatus

TABLE 70.—COST IN DOLLARS

NAME OF MACHINE	NEW OR SECOND-HAND	Kw. + R.P.M.				
		0.001	0.01	0.1	1.0	10.0
Direct-current generators and motors	New	85	280	1,150	5,500	..
Induction motors	New	100	260	850	3,500	..
Alternators	New	..	..	1,200	4,600	16,000
Turbo-alternators	New	..	..	..	37,000	136,000
Low-speed engines	New	Com	pound	..	6,000	17,700
High-speed engines	New	Com	pound	1,600	4,900	..
Low-speed engines	New	Sim	ple	..	3,200	13,500
High-speed engines	New	Sim	ple	680	2,530	..
Direct-current generators and motors	Second-hand	40	120	450	1,600	..
Induction motors	Second-hand	45	170	550	2,500	..
Alternators	Second-hand	..	140	450	2,200	8,000
Engine-driven direct-current and alternating-current generators	Second-hand	..	200	700	3,000	13,000

TABLE 71.—WEIGHT IN POUNDS

NAME OF MACHINE	Kw. + R.P.M.				
	0.001	0.01	0.1	1.0	10.0
Direct-current generators and motors	130	810	4,200	22,000	110,000
Induction motors	80	510	2,800	15,000	81,000
Alternators	130	810	4,200	20,000	90,000
Turbo-alternators	..	..	..	170,000	640,000
Low-speed engines	..	..	2,400	19,000	140,000
High-speed engines	..	..	4,500	31,000	..
Engine-driven direct-current and alternating-current generators	..	1,400	8,000	50,000	250,000

TABLE 72.—CENTS PER POUND

NAME OF MACHINE	NEW OR SECOND-HAND	Kw. + R.P.M.				
		0.001	0.01	0.1	1.0	10.0
Direct-current generators and motors	New	65	35	27	25	..
Induction motors	New	125	51	30	23	..
Alternators	New	..	..	29	23	18
Turbo-alternators	New	..	..	..	22	21
Low-speed engines	New	Com	pound	..	28	11
High-speed engines	New	Com	pound	36	15	..
Low-speed engines	New	Sim	ple	..	17	9
High-speed engines	New	Sim	ple	15	8	..
Direct-current generators and motors	Second-hand	31	15	11	7	..
Induction motors	Second-hand	56	33	20	17	..
Alternators	Second-hand	..	17	11	11	9
Engine-driven direct-current and alternating-current generators	Second-hand	..	14	9	6	5

TABLE 73.—DIAMETER—RESISTANCE, ETC., OF BARE WIRE FROM NO. 0000 TO 26

Am. Gauge B. & S. No.	Diam. Mils.	Area		Weight and Length Sp. Gr. 8 9			Resistance at 75° F.			
		Circular Mils. (d^2) 1 Mil. = .001 Inch	Square in. ($D^2 \times 7854$)	Lbs. Per 1,000 Ft.	Lbs. Per Mile	Feet Per Lb.	Ohms Per 1,000 Feet	Ohms Per Mile	Feet Per Ohm	Ohms Per Lb.
0000	460.000	211600.00	166190.	639.33	3375.7	1.56	.04906	.25903	20383.	.000076736
000	409.640	167800.00	131790.	507.01	2677.0	1.97	.06186	.32664	16165.	.00012039
00	364.800	133079.40	104520.	402.09	2123.0	2.49	.07801	.41187	12820.	.00019423
0	324.860	105592.50	82932.	319.04	1684.5	3.13	.09831	.51909	10409.	.00030772
1	289.300	83691.20	65733.	252.88	1335.2	3.95	.12404	.65490	8062.3	.00048994
2	257.680	66373.00	52130.	200.54	1058.8	4.99	.15640	.82582	6393.7	.00078045
3	229.420	52634.00	41399.	159.03	839.68	6.29	.19723	1.0414	5070.2	.0012406
4	204.310	41742.00	32784.	126.12	665.91	7.93	.24869	1.3131	4021.0	.0019721
5	181.940	33102.00	25998.	100.01	528.05	10.00	.31361	1.6558	3188.7	.0031361
6	162.020	26250.50	20617.	79.32	418.81	12.61	.39546	2.0881	2528.7	.0049868
7	144.280	20816.00	16349.	62.90	332.11	15.90	.49871	2.6331	2005.2	.0079294
8	128.490	16509.00	12966.	49.88	263.37	20.05	.62881	3.3201	1590.3	.012608
9	114.430	13094.00	10284.	39.56	208.88	25.28	.79281	4.1860	1261.3	.020042
10	101.890	10381.00	8153.2	31.37	165.63	31.38	1.	5.2800	1000.0	.031380
11	90.742	8234.00	6467.0	24.88	137.37	40.20	1.2607	6.6568	793.18	.050682
12	80.808	6529.90	5128.6	19.73	104.18	50.69	1.5898	8.3940	629.02	.080585
13	71.961	5178.38	4067.0	15.68	82.792	63.78	2.0037	10.5798	499.06	.127788
14	64.084	4106.76	3225.4	12.44	65.658	80.42	2.5266	13.3405	375.79	.203180
15	57.068	3256.76	2557.8	9.86	52.069	101.40	3.1860	16.8223	313.87	.323079
16	50.820	2582.67	2028.4	7.82	41.292	127.87	4.0176	21.2130	248.90	.513737
17	45.257	2048.20	1608.6	6.20	32.746	161.24	5.0660	26.7485	197.39	.816839
18	40.303	1624.33	1275.7	4.92	25.970	203.31	6.3880	33.7285	156.54	1.298764
19	35.890	1288.09	1011.6	3.90	20.594	256.39	8.0555	42.5329	124.14	2.065312
20	31.961	1021.44	802.2	3.09	16.331	323.32	10.1584	53.6362	98.44	3.284374
21	28.462	810.09	636.2	2.45	12.952	407.67	12.8088	67.6302	78.07	5.221775
22	25.347	642.47	504.6	1.95	10.272	514.03	16.1504	85.2343	61.92	8.301819
23	22.571	509.45	400.1	1.54	8.1450	648.25	20.3674	107.540	49.10	13.20312
24	20.100	404.01	317.3	1.22	6.4593	817.43	25.6830	135.606	38.94	20.99405
25	17.900	320.41	251.6	.97	5.1227	1030.71	32.3833	170.984	30.88	33.37780
26	15.940	254.08	199.5	.77	4.0623	1299.77	40.8377	215.623	24.49	53.07946

TABLE 74.—BARE CONCENTRIC-LAY CABLES OF STANDARD ANNEALED COPPER (ENGLISH UNITS)

SIZE OF CABLE		OHMS PER 1000 FEET		POUNDS PER 1000 FEET	STANDARD CONCENTRIC STRANDING			FLEXIBLE CONCENTRIC STRANDING		
Circular Mils	A. W. G. No.	25° C (=77° F)	65° C (=149° F)		Number of Wires	Diameter of Wires, in Mils	Outside Diameter, in Mils	Number of Wires	Diameter of Wires, in Mils	Outside Diameter, in Mils
2 000 000		0.005 39	0.006 22	6180.	127	125.5	1631.	169	108.8	1632.
1 900 000		.005 68	.006 55	5870.	127	122.3	1590.	169	106.0	1590.
1 800 000		.005 99	.006 92	5560.	127	119.1	1548.	169	103.2	1548.
1 700 000		.006 34	.007 32	5250.	127	115.7	1504.	169	100.3	1504.
1 600 000		.006 74	.007 78	4940.	127	112.2	1459.	169	97.3	1460.
1 500 000		.007 19	.008 30	4630.	91	128.4	1412.	127	108.7	1413.
1 400 000		.007 70	.008 89	4320.	91	124.0	1364.	127	105.0	1365.
1 300 000		.008 30	.009 58	4010.	91	119.5	1315.	127	101.2	1315.
1 200 000		.008 99	.0104	3710.	91	114.8	1263.	127	97.2	1264.
1 100 000		.009 81	.0114	3400.	91	109.9	1209.	127	93.1	1210.
1 000 000		.0108	.0124	3090.	61	128.0	1152.	91	104.8	1153.
950 000		.0114	.0131	2930.	61	124.8	1123.	91	102.2	1124.
900 000		.0120	.0138	2780.	61	121.5	1093.	91	99.4	1094.
850 000		.0127	.0146	2620.	61	118.0	1062.	91	96.6	1063.
800 000		.0135	.0156	2470.	61	114.5	1031.	91	93.8	1031.
750 000		.0144	.0166	2320.	61	110.9	998.	91	90.8	999.
700 000		.0154	.0178	2160.	61	107.1	964.	91	87.7	965.
650 000		.0166	.0192	2010.	61	103.2	929.	91	84.5	930.
600 000		.0180	.0207	1850.	61	99.2	893.	91	81.2	893.
550 000		.0196	.0226	1700.	61	95.0	855.	91	77.7	855.
500 000		.0216	.0249	1540.	37	116.2	814.	61	90.5	815.
450 000		.0240	.0277	1390.	37	110.3	772.	61	85.9	773.
400 000		.0270	.0311	1240.	37	104.0	728.	61	81.0	729.
350 000		.0308	.0356	1080.	37	97.3	681.	61	75.7	682.
300 000		.0360	.0415	926.	37	90.0	630.	61	70.1	631.
250 000		.0431	.0498	772.	37	82.2	575.	61	64.0	576.
212 000	0000	.0509	.0587	653.	19	105.5	528.	37	75.6	533.
168 000	000	.0642	.0741	518.	19	94.0	470.	37	67.3	471.
133 000	00	.0811	.0936	411.	19	83.7	418.	37	60.0	420.
106 000	0	.102	.117	326.	19	74.5	373.	37	53.4	374.
83 700	1	.129	.149	258.	19	66.4	332.	37	47.6	333.
66 400	2	.162	.187	205.	7	97.4	292.	19	59.1	296.
52 600	3	.205	.237	163.	7	86.7	260.	19	52.6	263.
41 700	4	.259	.299	129.	7	77.2	232.	19	46.9	234.
33 100	5	.326	.376	102.	7	68.8	206.	19	41.7	209.
26 300	6	.410	.473	81.0	7	61.2	184.	19	37.2	186.
20 800	7	.519	.599	64.3	7	54.5	164.	19	33.1	166.
16 500	8	.654	.755	51.0	7	48.6	146.	19	29.5	147.

This table is taken from Circular No. 31, Copper Wire Tables, Third Edition, October 1, 1914, U. S. Bureau of Standards, and is in accord with standards adopted by the Standards Committee of the American Institute of Electrical Engineers, both in respect to the "Number of wires" and in respect to the correction for increase of resistance and mass due to the twist of the wires. The values given for "Ohms per 1000 feet" and "Pounds per 1000 feet" are 2 per cent. greater than for a solid rod of cross section equal to the total cross section of the wires of the cable. This increment of 2 per cent. means that the values are correct for cables having a lay of 1 in 15.7.

COPPER WIRE.—98 per cent. Pure Specific Gravity 8.89.

$$\text{Weight per 1,000 feet} = .003027 \times d^2 \text{ or } \frac{d^2}{330.353}$$

$$\text{Weight per mile} = .015983 \times d^2 \text{ or } \frac{d^2}{62{,}567}$$

$$\text{Resistance per 1,000 feet at 60° F.} = \frac{30{,}815}{W \text{ per 1,000 ft.}} \text{ or } \frac{10180.694}{d^2}$$

$$\text{Resistance per 1,000 feet at 75° F.} = \frac{31{,}804}{W \text{ per 1,000 ft.}} \text{ or } \frac{10507.4}{d^2}$$

Specific conductivity of pure copper is 100 (100 inches pure copper weighing 100 grains at 60° F. = 0.1516 ohms) of commercial copper, from 96 to 102 per cent. of standard.

The percentage of conductivity of copper is found by measuring the resistance of a sample of the same length and weight as the standard and at the same temperature. R = resistance of standard, r = the resistance of sample, $\frac{100\times R}{r}$ = per cent. conductivity.

TABLE 75.—EQUIVALENTS OF WIRES: B & S GAUGE

0000 = 2–0 = 4–3 = 8–6 = 16–9 = 32–12 = 64–15
000 = 2–1 = 4–4 = 8–7 = 16–10 = 32–13 = 64–16
00 = 2–2 = 4–5 = 8–8 = 16–11 = 32–14 = 64–17
0 = 2–3 = 4–6 = 8–9 = 16–12 = 32–15 =
1 = 2–4 = 4–7 = 8–10 = 16–13 = 32–16
2 = 2–5 = 4–8 = 8–11 = 16–14 = 32–17
3 = 2–6 = 4–9 = 8–12 = 16–15 = 32–18
4 = 2–7 = 4–10 = 8–13 = 16–16
5 = 2–8 = 4–11 = 8–14 = 16–17
6 = 2–9 = 4–12 = 8–15 = 16–18
7 = 2–10 = 4–13 = 8–16 =
8 = 2–11 = 4–14 = 8–17
9 = 2–12 = 4–15 = 8–18
10 = 2–13 = 4–16
11 = 2–14 = 4–17
12 = 2–15 = 4–18
13 = 2–16 = 4–19
14 = 2–17
15 = 2–18
16 = 2–19

TABLE 76.—DECIMAL EQUIVALENTS
8ths, 16ths, 32ds and 64ths of an Inch

8ths

1/8 = .125
1/4 = .250
3/8 = .375
1/2 = .500
5/8 = .625
3/4 = .750
7/8 = .875

16ths

1/16 = .0625
3/16 = .1875
5/16 = .3125
7/16 = .4375
9/16 = .5625
11/16 = .6875
13/16 = .8125
15/16 = .9375

32ds

1/32 = .03125
3/32 = .09375
5/32 = .15625
7/32 = .21875
9/32 = .28125
11/32 = .34375
13/32 = .40625
15/32 = .46875
17/32 = .53125
19/32 = .59375
21/32 = .65625
23/32 = .71875
25/32 = .78125
27/32 = .84375
29/32 = .90625
31/32 = .96875

64ths

1/64 = .015625
3/64 = .046875
5/64 = .078125
7/64 = .109375
9/64 = .140625
11/64 = .171875
13/64 = .203125
15/64 = .234375
17/64 = .265625
19/64 = .296875
21/64 = .328125
23/64 = .359375
25/64 = .390625
27/64 = .421875
29/64 = .453125
31/64 = .484375
33/64 = .515625
35/64 = .546875
37/64 = .578125
39/64 = .609375
41/64 = .640625
43/64 = .671875
45/64 = .703125
47/64 = .734375
49/64 = .765625
51/64 = .796875
53/64 = .828125
55/64 = .859375
57/64 = .890625
59/64 = .921875
61/64 = .953125
63/64 = .984375

TABLE 77.—WIRE GAUGES IN MILS

No.	Roeblings	Brown & Sharpe	Birmingham & Stubs	New British Standard	No.	Roeblings	Brown & Sharpe	Birmingham & Stubs	New British Standard
000,000	460.			464.	16	63.	50.82	65.	64.
00,000	430.			432.	17	54.	45.26	58.	56.
0,000	393.	460.	454.	400.	18	47.	40.3	49.	48.
000	362.	409.6	425.	372.	19	41.	35.89	42.	40.
00	331.	364.8	380.	348	20	35.	31.96	35.	36.
0	307.	324.9	340.	324.	21	32.	28.46	32.	32.
1	283.	289.3	300.	300.	22	28.	25.35	28.	28.
2	263.	257.6	284.	276.	23	25.	22.57	25.	24.
3	244.	229.4	259.	252.	24	23.	20.1	22.	22.
4	225.	204.3	238	232.	25	20.	17.9	20.	20.
5	207.	181.9	220.	212.	26	18.	15.94	18.	18.
6	192.	162.	203.	192.	27	17.	14.2	16.	16.4
7	177.	144.3	180.	176.	28	16.	12.64	14.	14.8
8	162.	128.5	165.	160.	29	15.	11.26	13.	13.6
9	148.	114.4	148.	144.	30	14.	10.03	12.	12.4
10	135.	101.9	134.	128.	31	13.5	8.93	10.	11.6
11	120.	90.74	120.	116.	32	13.	7.95	9.	10.8
12	105.	80.81	109.	104.	33	11.	7.08	8.	10.
13	92.	71.96	95.	92.	34	10.	6.3	7.	9.2
14	80.	64.08	83.	80.	35	9.5	5.62	5.	8.4
15	72.	57.07	72.	72.	36	9.	5.	4.	7.6

IV. CONVERSION FACTORS USEFUL IN HYDROELECTRIC WORK

(Weight of one cubic foot of water taken as 62.4 lb.)

One ft. head = 0.434 lb. per square inch pressure.
One hp. under one foot head = 8.83 second ft.
One kw. under one foot head = 11.82 second ft. (100%)
One acre per day = 1.815 sq. ft. per hour.
One acre per hour = 12.1 sq. ft. per second.
One cu. ft. per second under one foot head = 0.847 kw.
One cu. ft. per second under one foot head = 1.1135 hp. (100%)
One cu. ft. per second = 1.9835 acre ft. per day.
One cu. ft. per second = 102 meters per hour.
One cu. ft. per day = 1.18 liters per hour.
One acre ft. under one foot head = 1.022 kw. hours.
One cu. in. per second = 50 cu. ft. per day.
One liter per second = 127,132 cu. ft. per hour.
One acre ft. per day = 0.504 second ft.
One acre ft. per day = 1.815 cu. ft. per hour.
One acre ft. per hour = 726 cu. ft. per minute.
One acre ft. per hour = 12.1 second ft.
One in. in depth = 3,630 cu. ft. per acre.
One ft. in depth = 43,560 cu. ft. per acre.
One meter in depth = 142,913 cu. ft. per acre.
One in. of rain per month (30.45 days) = 0.8832 sec. ft. per sq. mile.
One in. of rain per year (365.25 days) = 0.0736 sec. ft. per sq. mile.
One cu. ft. per acre = 0.0002755 inch in depth.
One cu. in. per sq. ft. = 0.007 inch in depth.
One liter per sq. meter = 0.0394 inch in depth.

1,000,000 cu. ft. per acre per day = 0.0002657 ft. per second.
1,000,000 cu. ft. per acre per hour = 0.006377 ft. per second.
1,000,000 cu. ft. per acre per second = 1.98347 ft. per day.
One in. per hour = 87,120 cu. ft. per acre per day.
One in. per hour = 645.33 cu. ft. per sq. mile per second.
One ft. per hour = 7,744 cu. ft. per sq. mile per second.
One hp. hour = 1,980,000 ft. lbs.
One watt hour = 2,654.31 ft. lbs.
One meter hp. hour = 1,952,910 ft. lb.
One hp. = 550 ft. lb. per second.
One hp. = 1.0139 meter hp.
One watt = 0.00134 hp.
One meter hp. = 0.9863 hp.
One kw. = 1⅓ hp.
Specific gravity of sea water = 1.026.
Atmospheric pressure at sea level, average 14.7 lb.
Height of a column of mercury in a perfect vacuum at sea level = 29.9 in.
Height of a column of water in a perfect vacuum at sea level = 34.9 ft.

If the head of a column of water is expressed in feet and the pressure at the foot of the column in pounds (lbs.) per square inch, then

head = 2.31 x pressure
pressure = head ÷ 2.31
= 0.434 x head (independently of the size of column)

An approximate allowance for friction-head can be made by substituting 0.5 for 0.434, thus

total pressure = 0.5 x head (approximately)

If (d) is the diameter of a pipe and (l) the length, both in inches, then the capacity will be = 0.000455 $d^2 l$ cubic feet.

The weight of water in lbs. in a pipe is 0.0284 $d^2 l$.

The weight of water in a pipe one yard (36 in.) long will be 0.024 x $36d^2 = 1.022d^2$, that is, the weight of water in lbs. per yd. in a pipe can be taken as equal to the square of the diameter in inches with an error only of about 2 per cent.

Barometer in inches x 0.4908 = pressure per square inch.
Atmospheric pressure ¼ mile above sea level = 14.02 lbs. per sq. in.
Atmospheric pressure ½ mile above sea level = 13.33 lbs. per sq. in.
Atmospheric pressure ¾ mile above sea level = 12.66 lbs. per sq. in.
Atmospheric pressure 1.0 mile above sea level = 12.02 per sq. in.
Atmospheric pressure 1¼ mile above sea level = 11.42 lbs. per sq. in.
Atmospheric pressure 1½ mile above sea level = 10.88 lbs. per sq. in.
Atmospheric pressure 2.0 miles above sea level = 9.88 lbs. per sq. in.
The equivalent HEAD of water in lbs., is for
Sea level = 33.95 lbs.
Altitude, ¼ mile above sea level = 32.38 lbs.
½ mile above sea level = 30.79 lbs.
¾ mile above sea level = 29.24 lbs.
1.0 mile above sea level = 27.76 lbs.
1¼ miles above sea level = 26.38 lbs.
1½ miles above sea level = 25.13 lbs.
2.0 miles above sea level = 22.82 lbs.
One ft. of water 39.1 deg. F. = 62.425 lbs. on the sq. ft.
One ft. of water 39.1 deg. F. = 0.4335 lbs. on the sq. in.
One ft. of water 39.1 deg. F. = 0.0295 atmosphere.

One ft. of water 39.1 deg. F. = 0.8826 in. of mercury at 32 deg. F.
One ft. of water 39.1 deg. F. = 773.3 ft. of air at 32 deg. F.
One lb. on the sq. ft., at 39.1 deg. F. = 0.01602 ft. of water.
One lb. on the sq. in., at 39.1 deg. F. = 2.307 ft. of water.
One ft. of water at 62 deg. F. = 62.355 lbs. per sq. ft.
One ft. of water at 62 deg. F. = 0.433 lbs. per sq. in.
One in. of water at 62 deg. F. = 0.036 lbs. per sq. in.
One lb. of water on the sq. in. at 62 deg. F. = 2.3 ft. of water.
One ft. of water per second = 0.3048 meter per second.
One ft. of water per second = 0.018288 kilometer per minute.
One ft. of water per second = 0.011364 mile per minute.
One meter length = 3.28 ft.
One kilometer length = 3,280 ft.
One kilometer length = 0.62137 mile.
One ft. length = 0.3048 meter.
One meter per second = 3.28 ft. per second.
One meter per second = 0.06 kilometer per minute.
One meter per second = 0.037283 mile per minute.
One kilometer per minute = 54.682 ft. per second.
One kilometer per minute = 16.667 meters per second.
One kilometer per minute = 0.62138 mile per minute.
One mile per minute = 88.0 ft. per second.
One mile per minute = 26.822 meters per second.
One mile per minute = 1.6 kilometers per minute.
One liter (1 cu. decimeter) = 61.023 cu. inches.
One liter (1 cu. decimeter) = 0.03531 cu. ft.
One liter (1 cu. decimeter) = 2.202 lbs. of water at 62 deg. F.
One cu. ft. capacity = 28.317 liters.
One cu. yd. (27 cu. ft.) = 764.559 liters.
One gallon (British) = 4.543 liters.
One gallon (British) = 277.274 cu in.
One gallon (American) = 3.785 liters.
One gallon (American) = 231.0 cu. in.
One acre = 43,560 sq. ft.
One acre = 208.71 ft. on one side of square.
One acre = 4,840 sq. yds.
640 acres = 1 sq. mile.
247.11 acres = 1 sq. kilometer.
2.4711 acres = 1 hectare.

V. OUTLINE OF HYDROELECTRIC DEVELOPMENT AND NOMENCLATURE

GENERAL FEATURES OF THE SYSTEM:

- (A) Head-works.
- (B) Forebay.
- (C) Power-house.

PROTECTION OF THE SYSTEM:

- (a) Expansion joints.
- (b) Air-valves.
- (c) Sluice-gates.

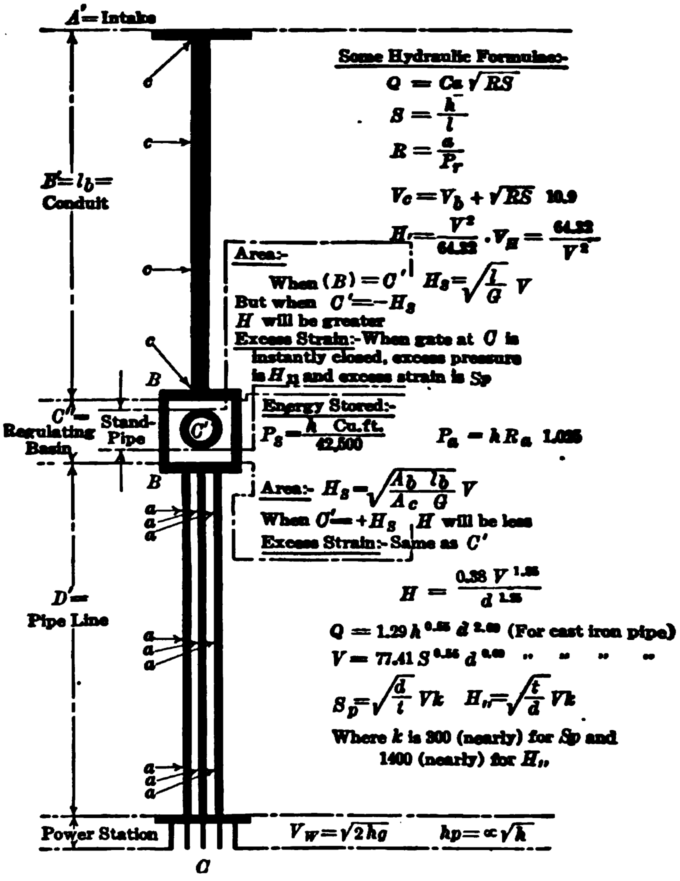

A'= Intake
c
c
c
c
$B'=l_b=$ Conduit
B
C'= Regulating Basin
Stand-Pipe
C'
B
a a a
a a a
a a a
D'= Pipe Line
Power Station
C
Some Hydraulic Formulae:-
$Q = Ca\sqrt{RS}$
$S = \frac{h}{l}$
$R = \frac{a}{P_r}$
$V_c = V_b + \sqrt{RS}$ 10.9
$H_f = \frac{V^2}{64.32}.V_H = \frac{64.32}{V^2}$
Area:-
When $(B) = C'$ $H_S = \sqrt{\frac{l}{G}}\,V$
But when $C' = -H_S$
H will be greater
Excess Strain:-When gate at C is instantly closed, excess pressure is $H_{\prime\prime}$ and excess strain is S_p
Energy Stored:-
$P_S = \frac{h \text{ Cu.ft.}}{42,500}$
$P_a = h R_a$ 1.026
Area:- $H_S = \sqrt{\frac{A_b}{A_c}\frac{l_b}{G}}\,V$
When $C' = +H_S$ H will be less
Excess Strain:-Same as C'
$H = \frac{0.38\,V^{1.86}}{d^{1.25}}$
$Q = 1.29\,h^{0.55}\,d^{2.60}$ (For cast iron pipe)
$V = 77.41\,S^{0.56}\,d^{0.60}$ " " " "
$S_p = \sqrt{\frac{d}{t}}\,Vk$ $H_{\prime\prime} = \sqrt{\frac{t}{d}}\,Vk$
Where k is 300 (nearly) for S_p and 1400 (nearly) for $H_{\prime\prime}$
$V_W = \sqrt{2hg}$
$hp = \propto \sqrt{h}$

Fig. 210.—Essential Features of a Hydraulic System

PARTS OF THE SYSTEM:

INTAKE (A′).—Other things being equal, the intake should be located at the dam and be a part of it.

CONDUIT (B′).—This may be of any combination—flume, canal, tunnel or earth-ditch, and should be of such a grade as to insure safety.

SURGE- OR STANDPIPE (C′).—This should not be of a less size than the total area of penstock pipes and much larger if possible to insure satisfactory operating conditions. In every case (C″) is much preferable.

REGULATING BASIN (C″).—This should always be used in preference to a standpipe. Its use will not only reduce the strain on the pressure pipes, but it may be drawn from as required during heavy overloads, or other short-period calls for more power at the power-house. It may also receive water to take care of loads during summer droughts, etc.

PENSTOCK (pressure pipes) (D′).—This may consist of either reinforced concrete (wet or dry mix) pipes, steel or iron pipes, or wooden-stave pipes, with expansion joints and air valves properly located along the pipe line.

APPLIED FORMULÆ: A number of formulæ are used for hydraulic calculations. In fact, taking only the varied formula for discharge coefficient c, reduced to the form $V=c\sqrt{RS}$, there are about 20 different formulæ from which to choose, as the Smith, Williams, Bazin, Unwin, Kutter, Flamant, Lampe, Darcy, Moritz, Hawksley, Weisback, Lawford, Prony, Nelville, Fanning, Eytelwein, Bruges, Crimp, and Taylor, etc. Those formulæ are given which are in common use on hydroelectric systems.

KEY TO SYMBOLS USED IN FORMULAS OF FIG. 210

A_c = Surge-pipe area. If A_b equals A_c then $H_s=V\sqrt{l_b+G}$

a = Cross-sectional area of conduit.

C = Regulating basin or reservoir. Where this is constructed and used, the standpipe is of no use.

C_1 = Standpipe. This is not employed where a regulating basin has been provided.

d = Diameter of pipe in inches.

d_1 = Diameter of pipe in feet.

G = Equal to 32.16.

h = Head in feet.

H = Head loss by friction.

$hp.$ = Horse-power.

H_1 = Theoretical head due to velocity of water.

H_p = Head due to pressure.

H_{11} = Excess pressure on pipe in feet of head due to sudden stoppage of flow.

H_s = Maximum height of water in surge-pipe when all the energy is given up.

H_t = Total head in feet; where H_d is the distance above datum line in ft., and p is pressure in lbs. per sq. ft.

$+H_s$ = Greater than H_s.

$-H_s$ = Less than H_s.

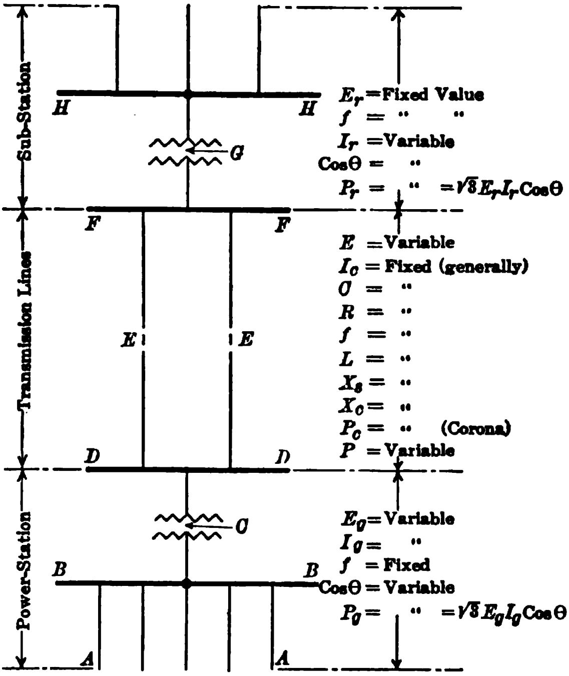
l_b = Total length of conduit.

l_d = Total length of pipe line.

P_a = Theoretical energy in acre-feet per kw.-hour; where R_a is the number of acres of regulating basin area per ft. depth. For any other efficiency below 100 per cent. multiply number by given efficiency; as, for 80 per cent. is $0.025 \text{x}\ 0.80=0.82$.

P^1_{m1} = Stored energy in conduit or pipe line.

P_m = Pressure increase per sq. in. at the bottom end of pipe line.



A = Power-House Generators
B = " " Low-Voltage Buses
C = " " Step-up Transformers
D = " " High-Voltage Buses
E = Transmission Lines
F = Sub-Station High-Voltage Buses
G = " " Step-down Transformers
H " " Low-Voltage Buses

Fig. 211.—Essential Features of a Transmission System

P_s = Theoretical energy in kw.-hours stored in regulating basin. For any percentage below 100 per cent. divide the divisor by given percentage; as, 80 per cent. eff. is $42{,}500 \div 0.80 = 50{,}000$-kw.-hours.
P_r = Wet perimeter of conduit.
Q = Quantity of water discharged in cu. ft. per second.
R = Mean hydraulic radius, $= a \div Pr$
R_p = Hydraulic mean radius in pipe, equal to 0.25 diameter of pipe.
s = Fall of water surface in any distance; sine of the angle of slope.
S = Hydraulic slope $= h \div l$.
S_p = Excess strain in pipe in lbs. per sq. in. due to sudden stoppage of flow.
t = Thickness of pipe in inches.
V = Velocity in feet per second (dimensions in feet).
V_c = Slope-bottom and mean velocity in conduit.
V_H = Velocity-head in pipe line.
v = Velocity in feet per second (using constant coefficient).

TABLE 78.—MAXIMUM TRANSMISSION VOLTAGES IN THE UNITED STATES—1916

STATE	MAXIMUM TRANSMISSION VOLTAGE	STATE	MAXIMUM TRANSMISSION VOLTAGE
Alabama	110,000	Nebraska	33,000
Arizona	45,000	Nevada	66,000
Arkansas	13,200	New Hampshire	15,000
California	150,000	New Jersey	33,000
Colorado	100,000	New Mexico	2,300
Connecticut	33,000	New York	110,000
Delaware	2,300	North Carolina	100,000
Florida	6,600	North Dakota	6,600
Georgia	110,000	Ohio	33,000
Idaho	44,000	Oklahoma	6,600
Illinois	66,000	Oregon	66,000
Indiana	35,000	Pennsylvania	125,000
Iowa	35,000	Rhode Island	110,000
Kansas	60,000	South Carolina	66,000
Kentucky	33,000	South Dakota	26,000
Louisiana	6,600	Tennessee	120,000
Maine	33,000	Texas	60,000
Maryland	33,000	Utah	130,000
Massachusetts	110,000	Vermont	66,000
Michigan	140,000	Virginia	44,000
Minnesota	40,000	Washington	66,000
Mississippi	13,200	West Virginia	88,000
Missouri	110,000	Wisconsin	66,000
Montana	102,000	Wyoming	22,000

V. STATION AND SYSTEM ARRANGEMENTS AND CIRCUITS

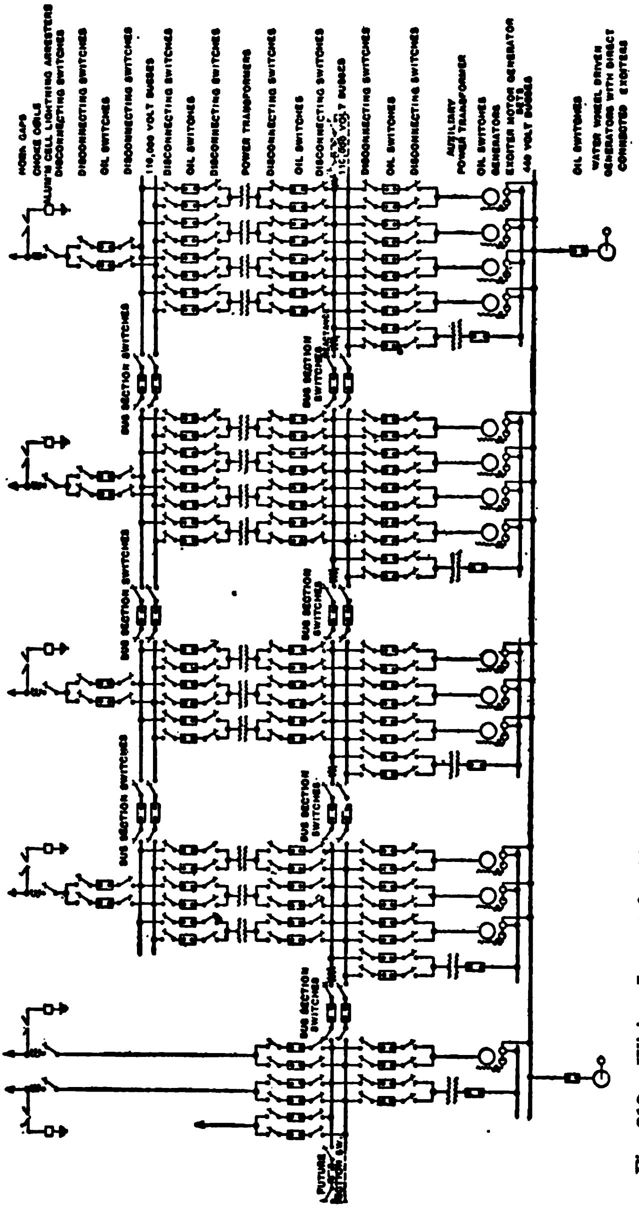


Fig. 212.—Wiring Layout for 110,000 Volt Generating Station Showing the Use of Reactance in the Bus Sections

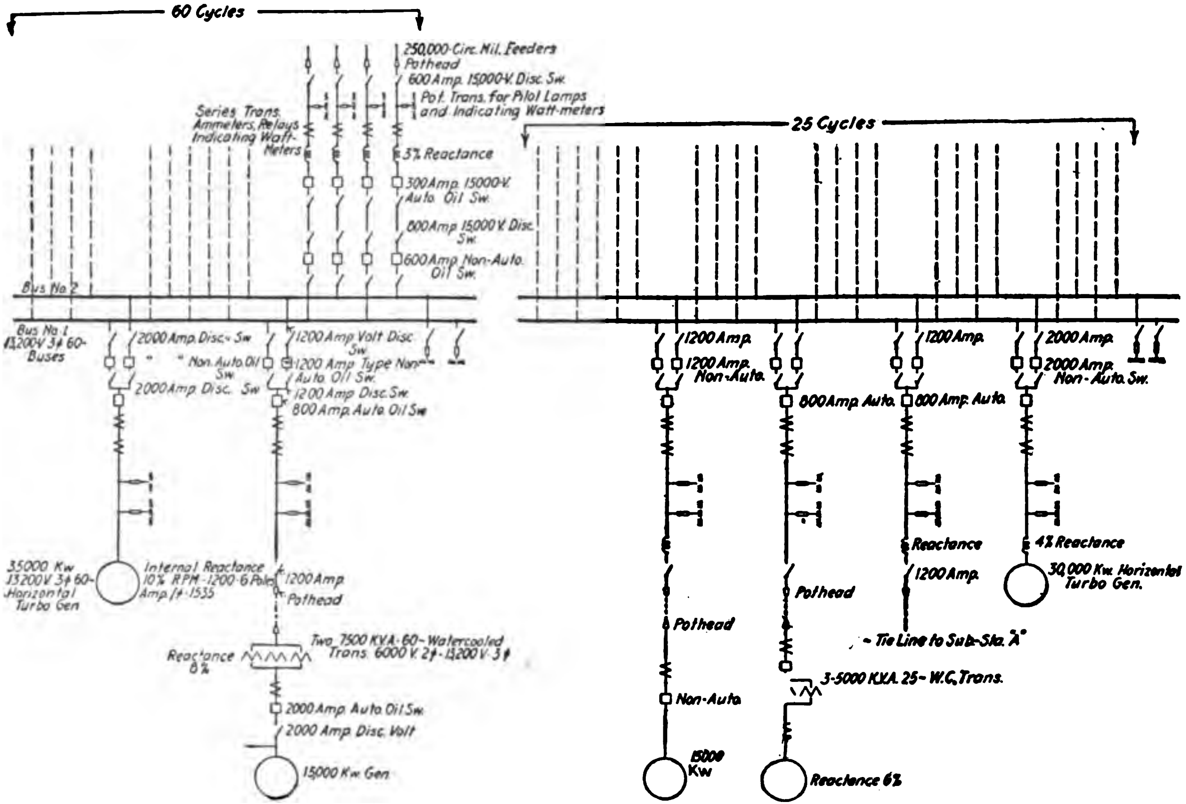

60 Cycles
25 Cycles
250,000-Circ. Mil. Feeders
Pothead
600 Amp. 15,000-V. Disc. Sw.
Pot. Trans. for Pilot Lamps and Indicating Watt-meters
Series Trans. Ammeters, Relays Indicating Watt-Meters
3% Reactance
300 Amp. 15000-V. Auto. Oil Sw.
800 Amp 15,000 V. Disc. Sw.
600 Amp Non-Auto. Oil Sw.
Bus No 2
Bus No. 1 13,200-V 3ϕ 60- Buses
2000 Amp. Disc.- Sw.
" " Non. Auto. Oil Sw.
2000 Amp. Disc. Sw
1200 Amp Volt Disc. Sw.
1200 Amp Type Non-Auto. Oil Sw.
1200 Amp Disc. Sw.
800 Amp. Auto. Oil Sw.
35000 Kw 13200 V. 3ϕ 60- Horizontal Turbo Gen
Internal Reactance 10% RPM -1200 -6 Poles Amp. 1ϕ -1535
1200 Amp.
Pothead
Two 7500 K.V.A.-60-Watercooled Trans. 6000 V. 2ϕ -13,200 V.-3ϕ
Reactance 8%
2000 Amp. Auto Oil Sw.
2000 Amp. Disc. Volt
15,000 Kw Gen.
1200 Amp.
1200 Amp. Non-Auto.
800 Amp. Auto.
800 Amp. Auto.
1200 Amp.
2000 Amp.
2000 Amp. Non-Auto. Sw.
Reactance
4% Reactance
1200 Amp.
30,000 Kw. Horizontal Turbo Gen.
Pothead
Pothead
Tie Line to Sub-Sta. "A"
3-5000 K.V.A. 25-W.C. Trans.
Non-Auto
15000 Kw
Reactance 6%

Fig. 213.—Arrangement of 60 Cycle and 25 Cycle Buses in a Large Station

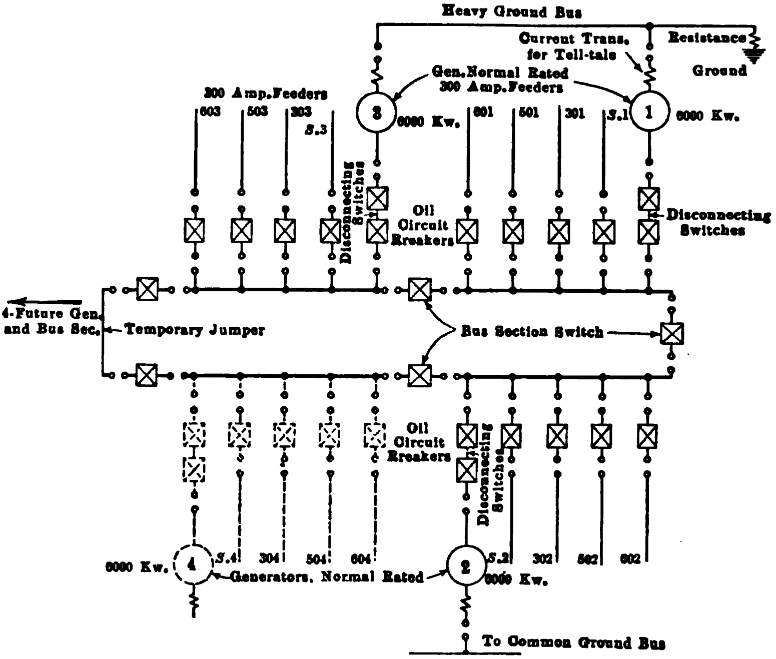


Fig. 214.—System of Connections for a 25,000 Kw. Generating Station

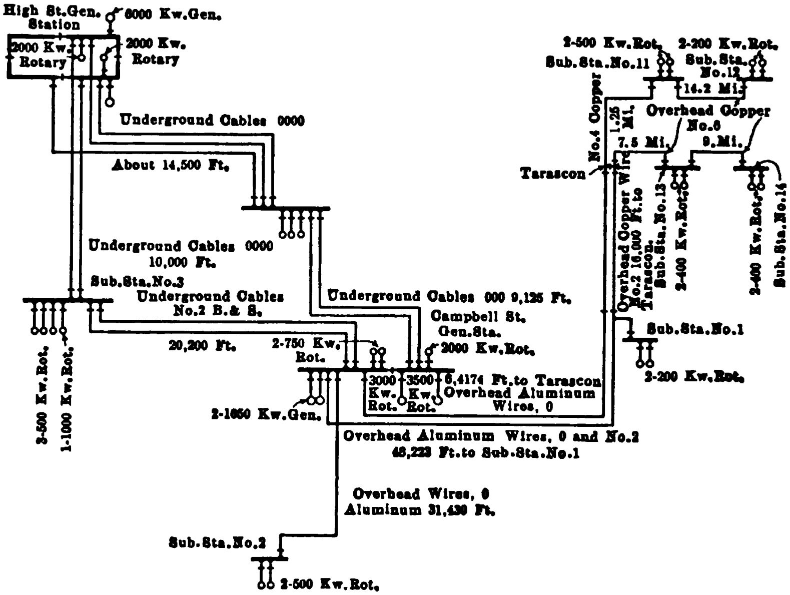


Fig. 215.—Complete System Connections Showing Generating Stations, Feeder System and Substations

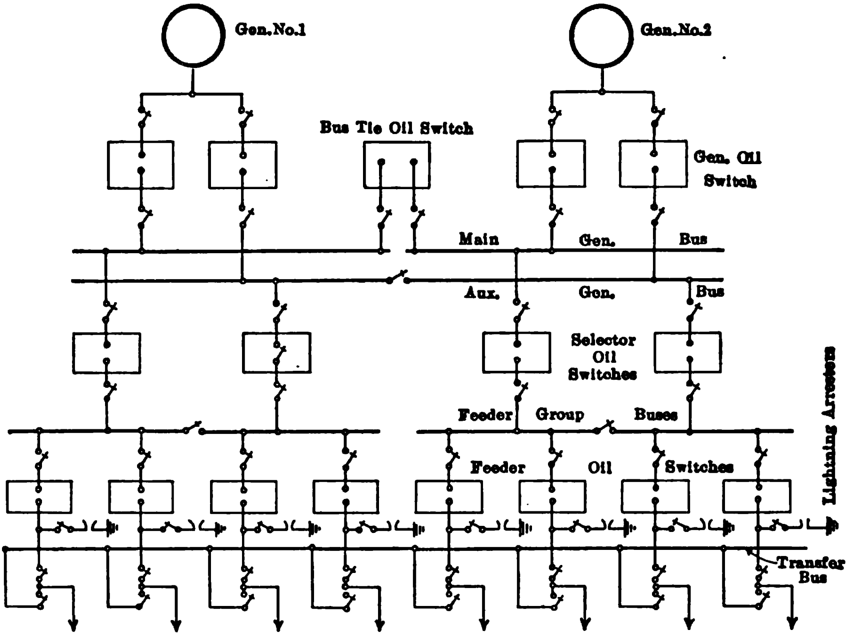


Fig. 216.—Bus Layout of Burlington Station of Public Service Company which Supplies Energy at 13,200 Volts to a Distribution System in Southern New Jersey

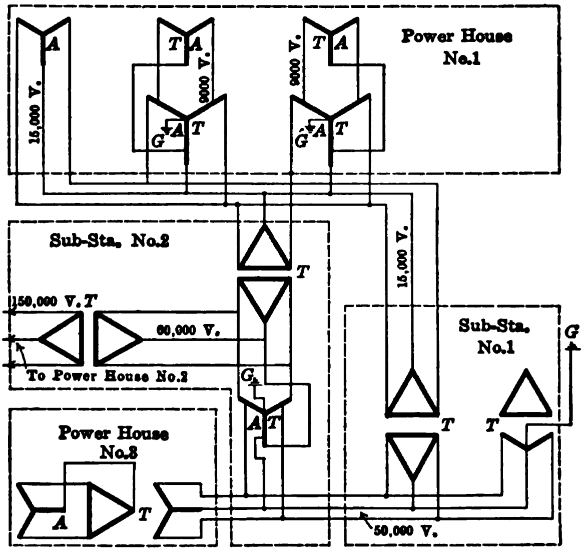


Fig. 217.—System Arrangements Showing Several Interconnected Generating Stations and Substations of Different System Connections (Delta and Star) and Different Voltages

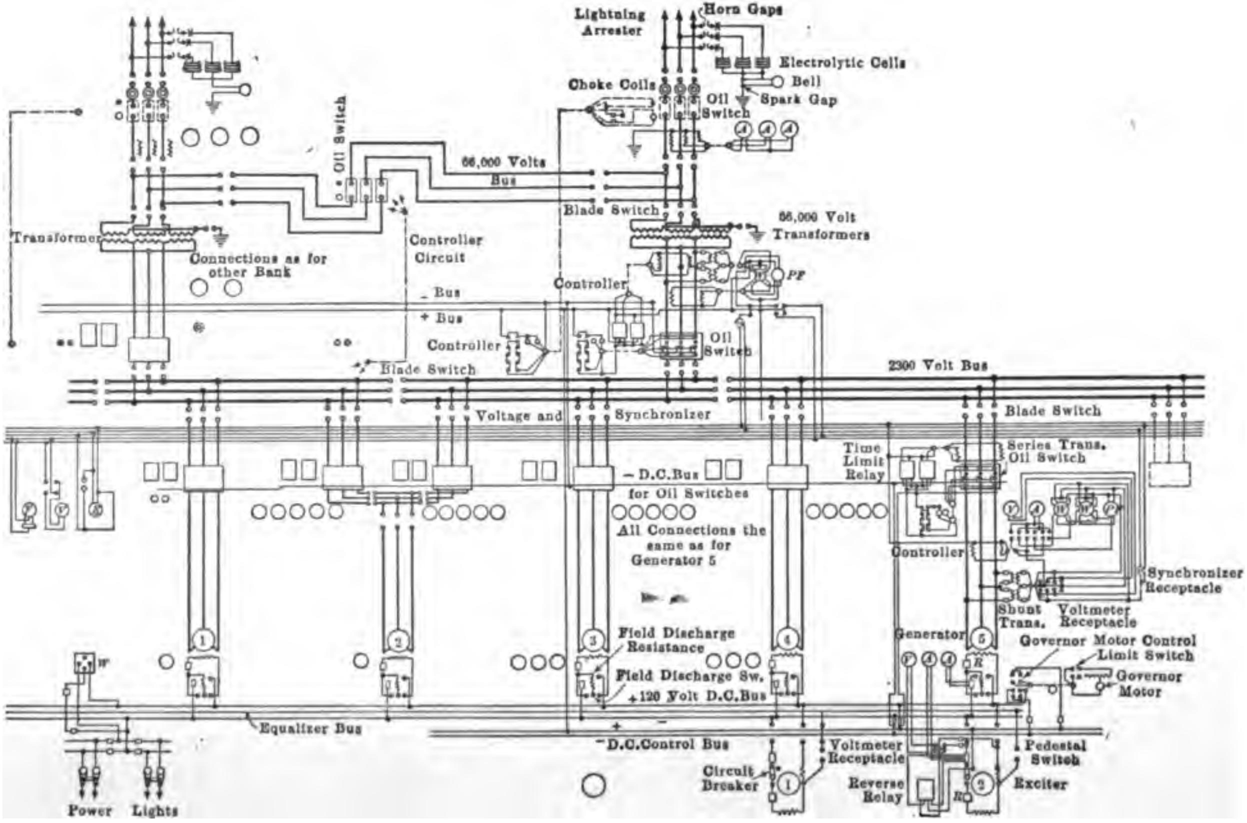


Fig. 218.—Arrangements of Circuits for a 66,000 Volt Generating Station

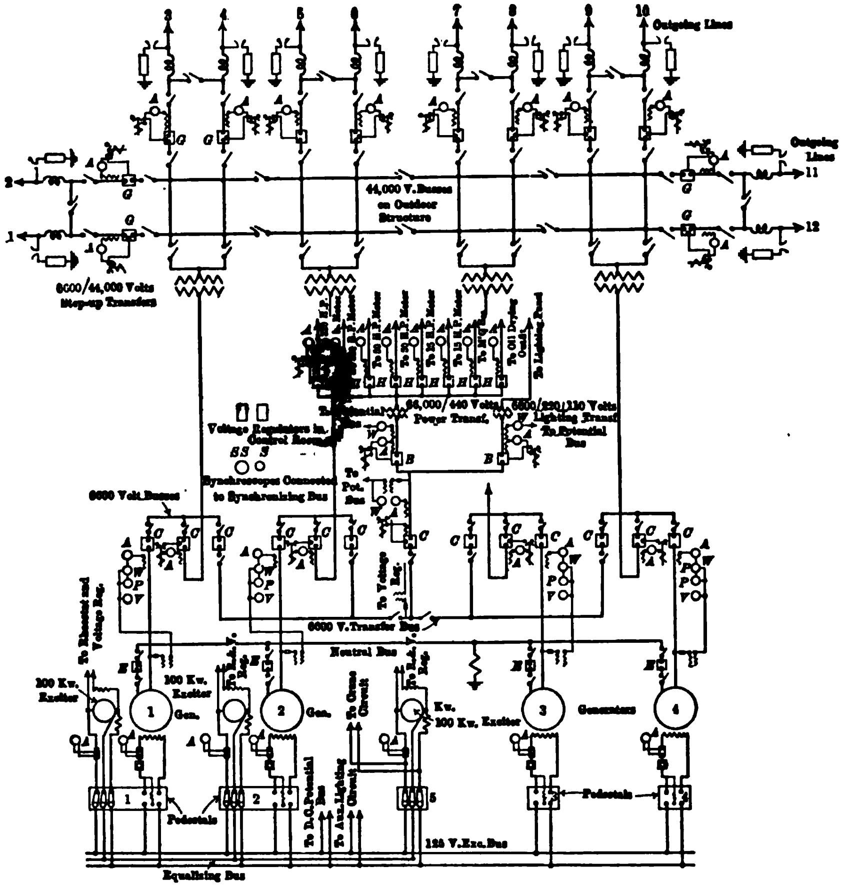


Fig. 219.—Arrangements of Circuits in the 25,000 Kw. Cabin Creek Generating Station of the Virginia Power Company that Furnishes Energy to West Virginia Coal Mines

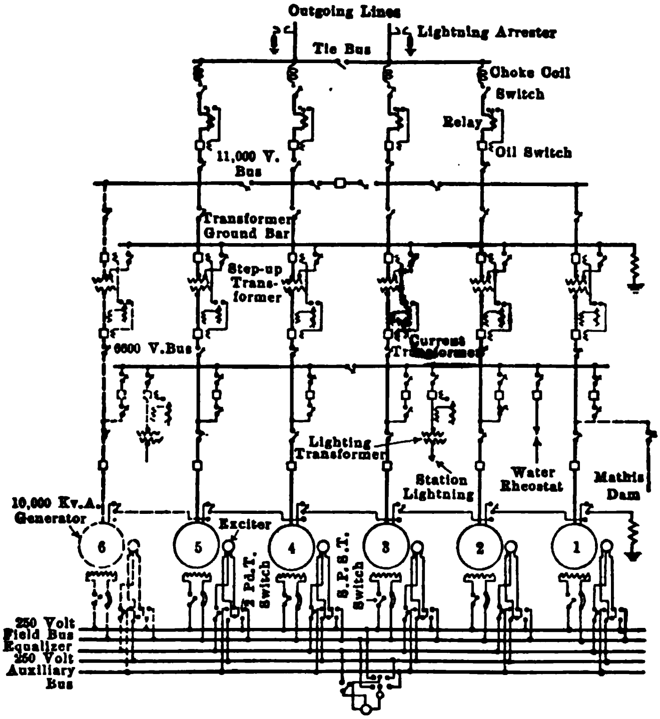


Fig. 220.—Arrangements of Circuits for a 50,000 Kw. Generating Station

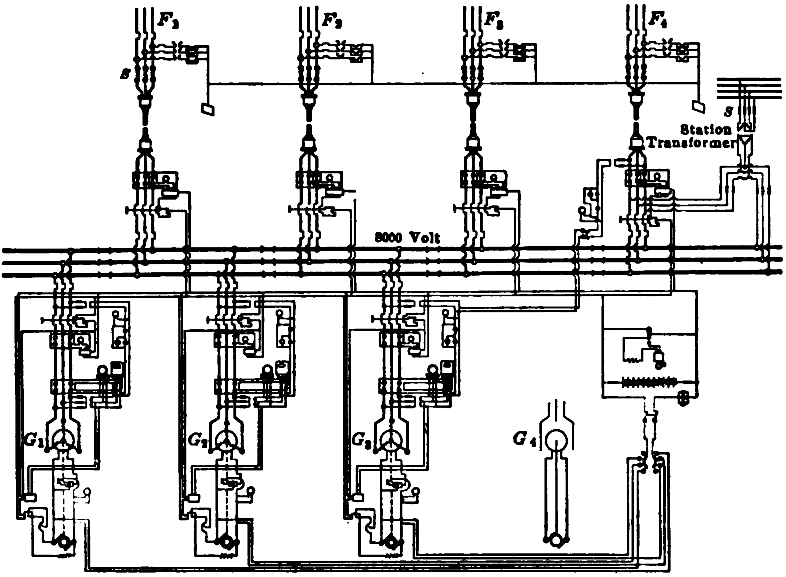


Fig. 221.—System of Connections Showing Special Exciter Arrangements for a Hydro-electric Plant Containing 4–10,000 Hp. Units

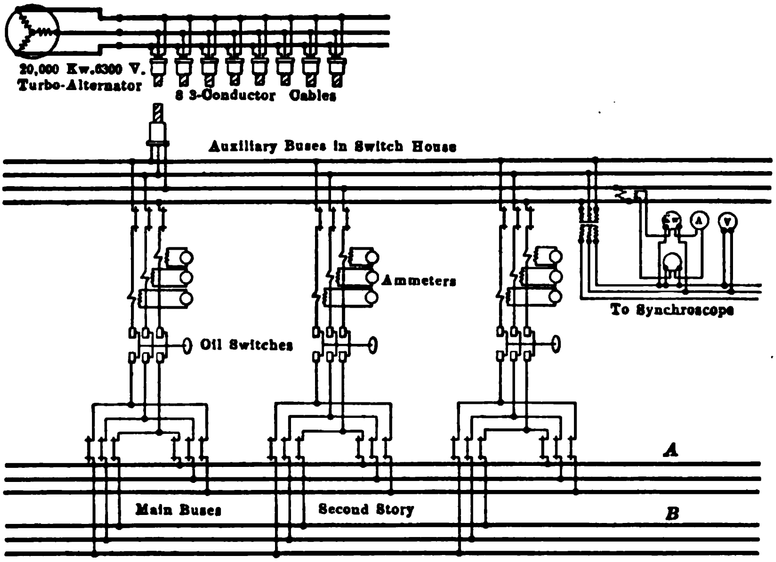


Fig. 222.—Circuits in a Large Switch-house of a Large Power System

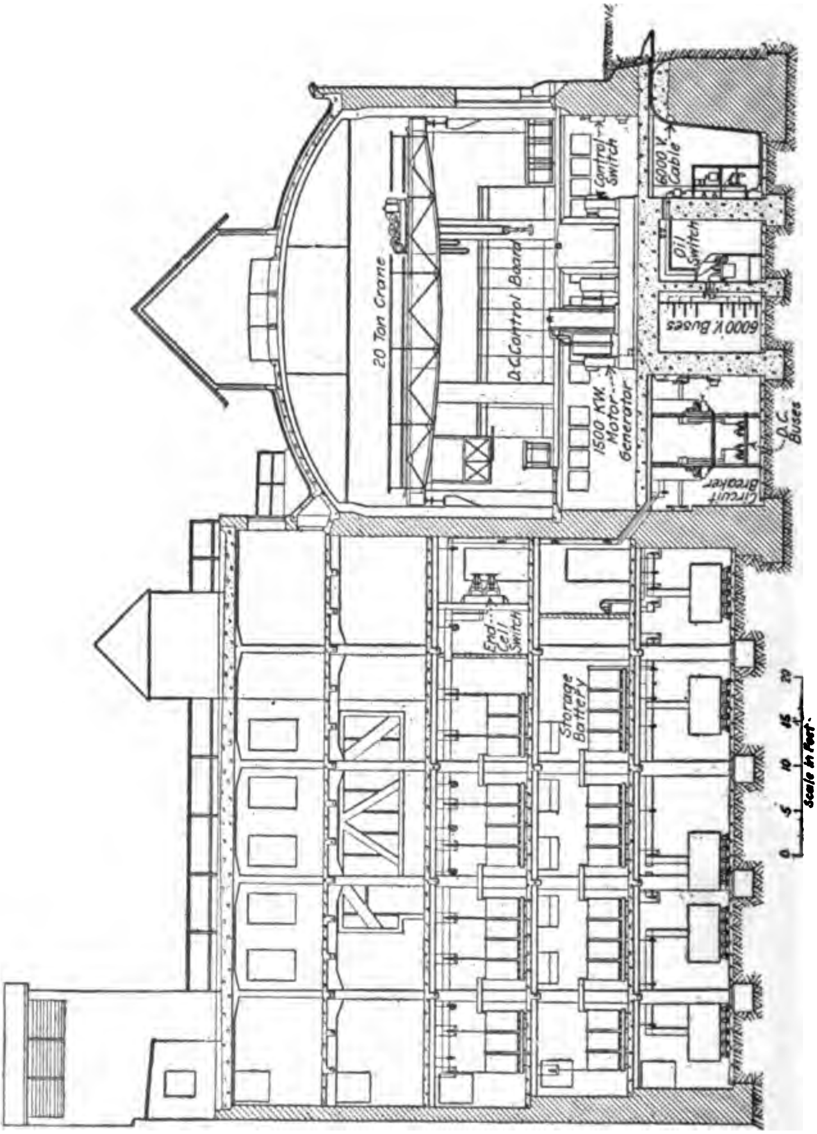


Fig. 223.—Section through a 9,000 Kw. Substation with a Large Storage Battery Annex

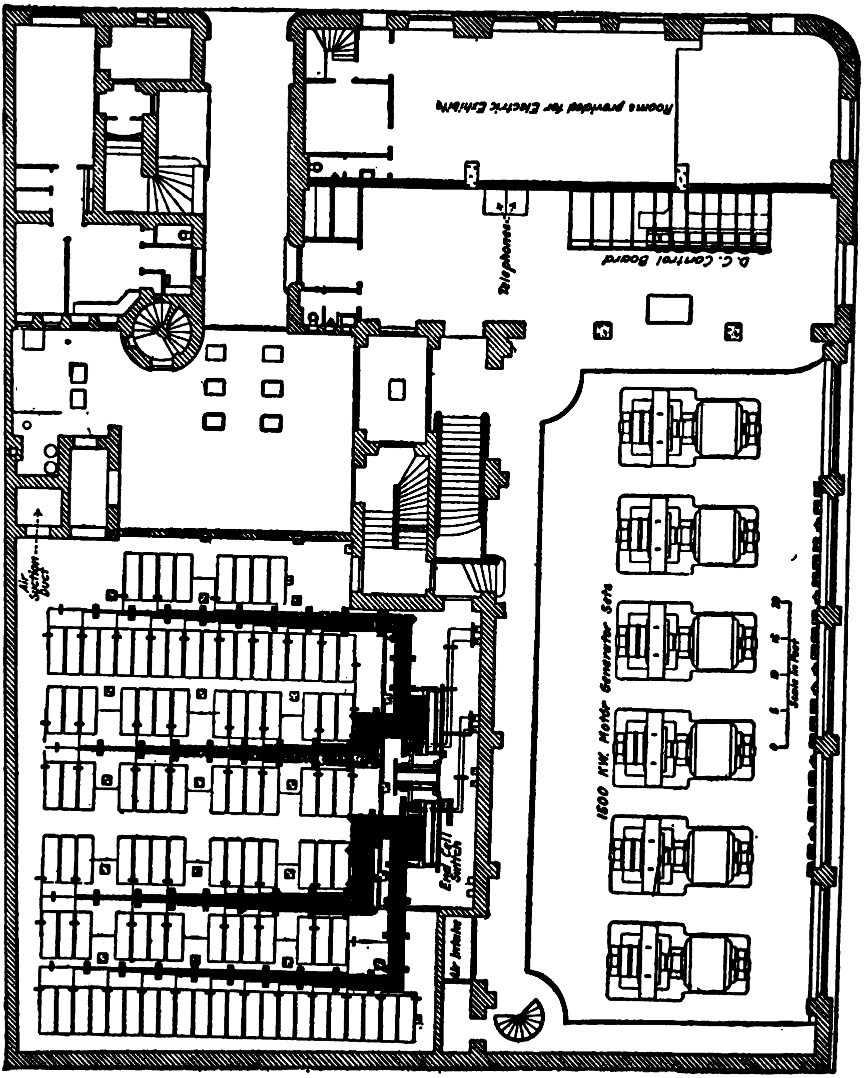


Fig. 224.—Plan of a 9,000 Kw. Substation with a Large Storage Battery Annex

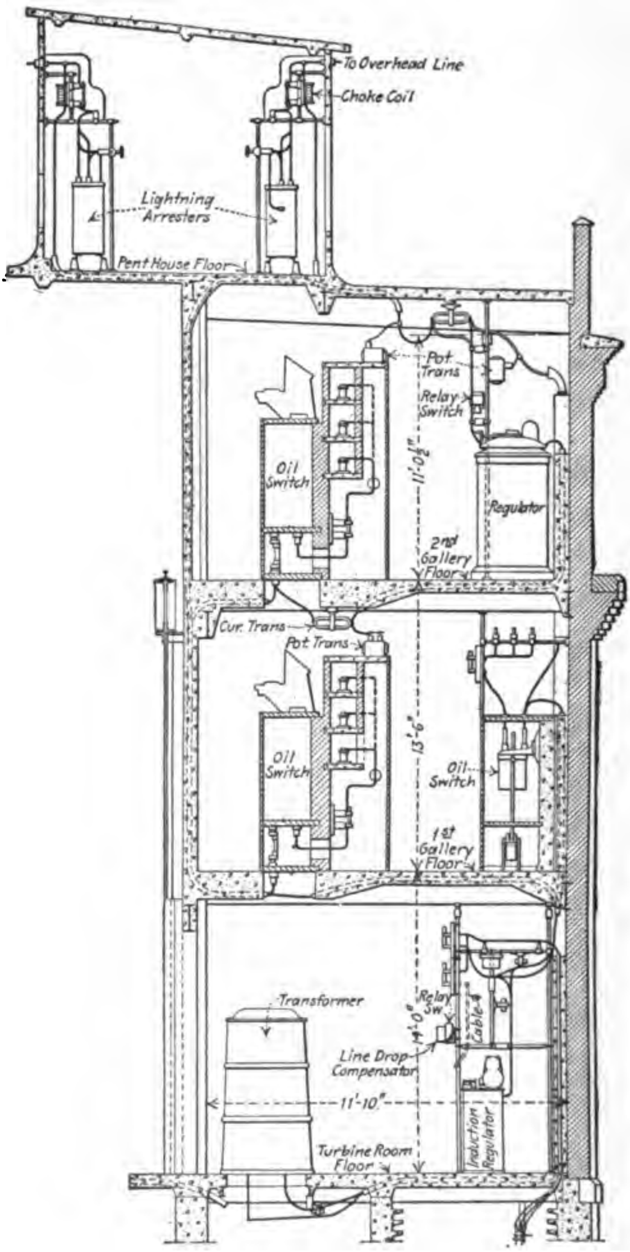
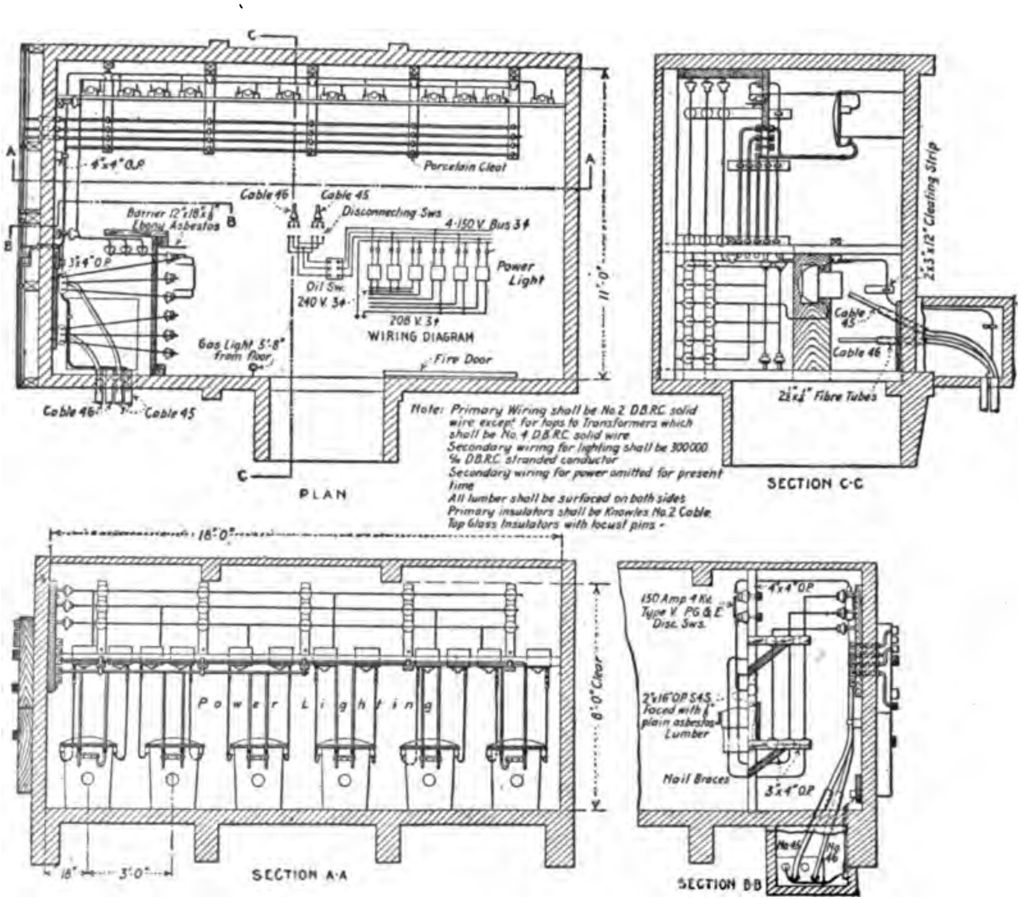


Fig. 225.—Section through Generating Station of Louisville (Ky.) Gas and Electric Company Showing Oil Switch Galleries



Note: Primary Wiring shall be No. 2 D.B.R.C. solid wire except for taps to Transformers which shall be No. 4 D.B.R.C. solid wire
Secondary wiring for lighting shall be 300000 ¾ D.B.R.C. stranded conductor
Secondary wiring for power omitted for present time
All lumber shall be surfaced on both sides
Primary insulators shall be Knowles No. 2 Cable Top Glass Insulators with locust pins -

Fig. 226.—Arrangement of Primary Distribution Transformer Vaults

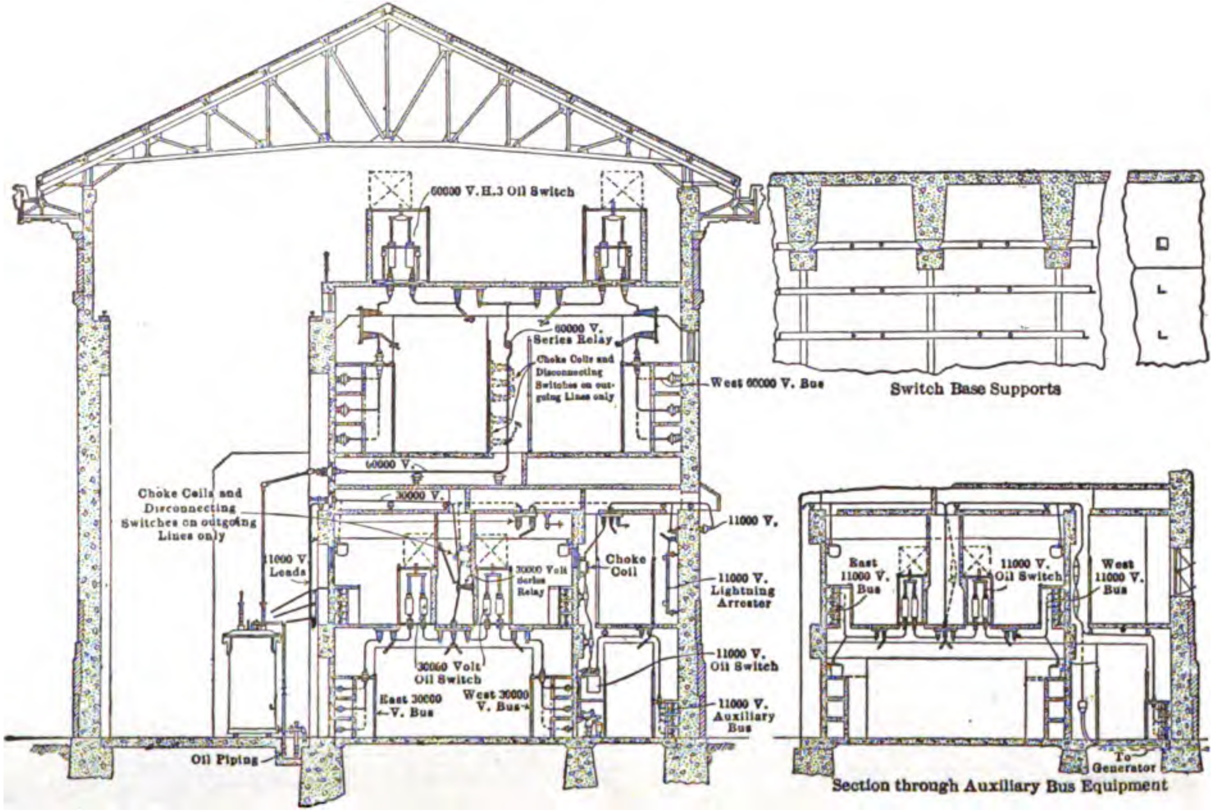


Fig. 227.—Large High Voltage Substation Designed to Meet the Requirements of Three Different Voltages (Long Beach Station of Southern California Edison Company)

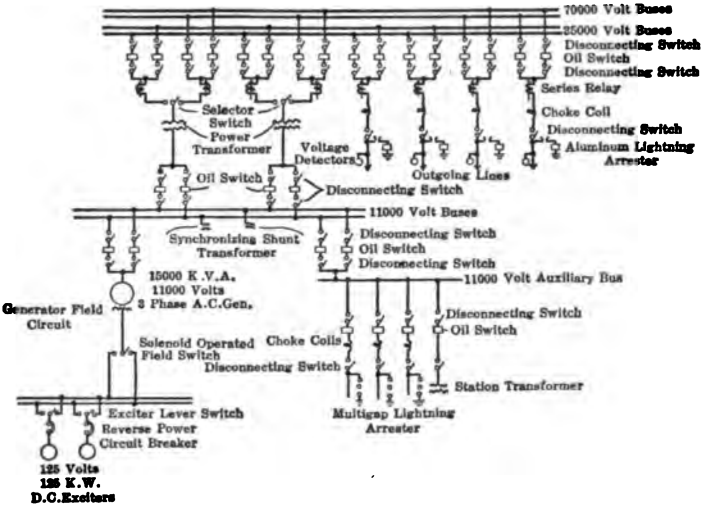


Fig. 228.—Circuits of Long Beach Steam Station of Southern California Edison Company, an Auxiliary to Hydroelectric Stations

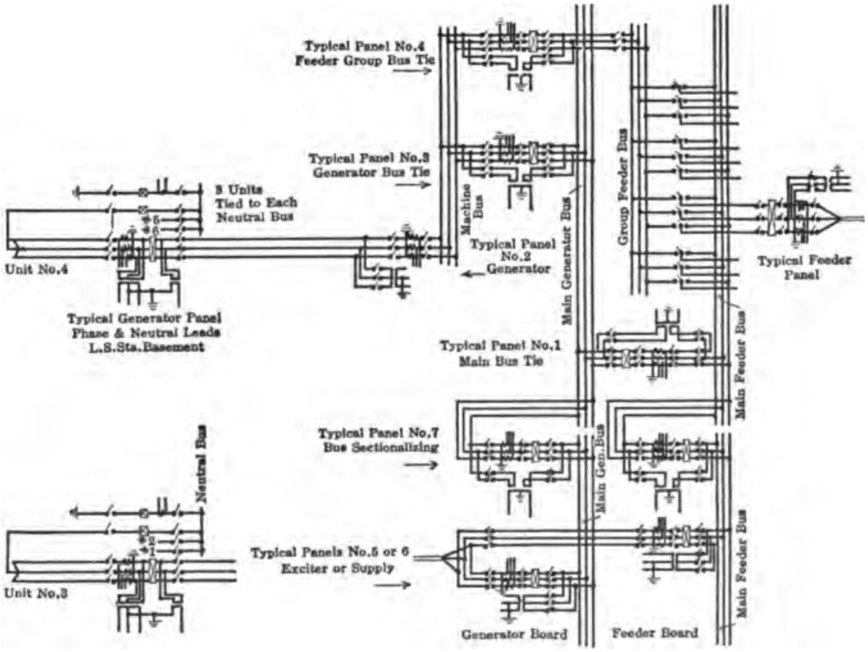


Fig. 229.—High Tension Wiring of Lake Shore Steam Station of Cleveland Electric Illuminating Company

Two 14,000 kw. and one 9,000 kw., 11,000 volt, three-phase, 60 cycle turbo-generators are operated. Two neutral buses are arranged for connecting to three machines and ground.

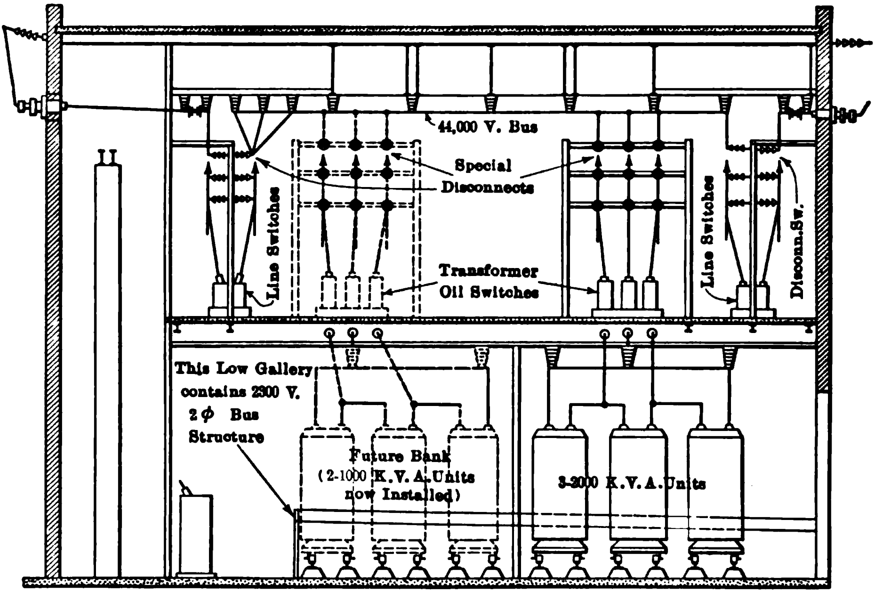


Fig. 230.—Method of Connecting Switches and Transformers by Open-Work Buses in Augusta (Ga.), Substation of Georgia-Carolina Company

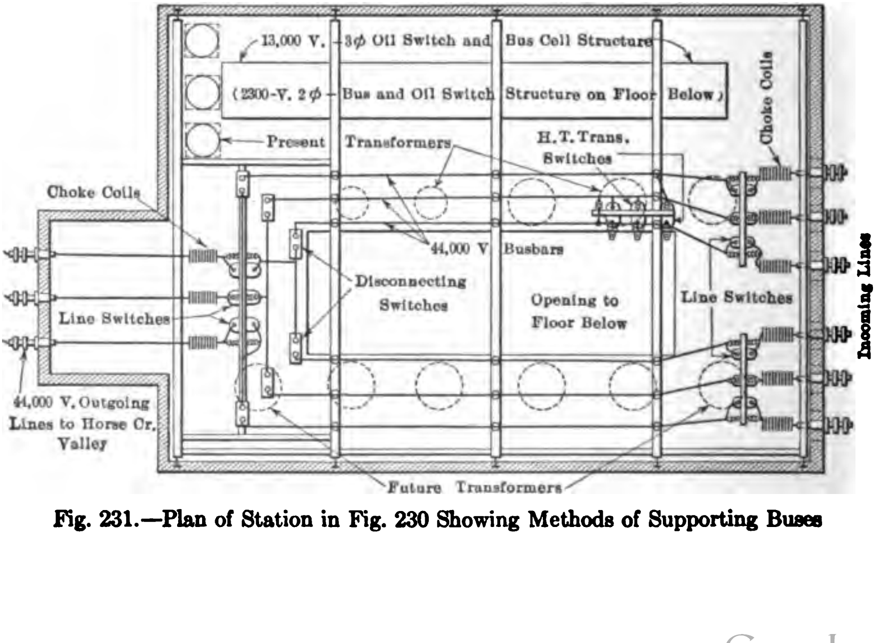


Fig. 231.—Plan of Station in Fig. 230 Showing Methods of Supporting Buses

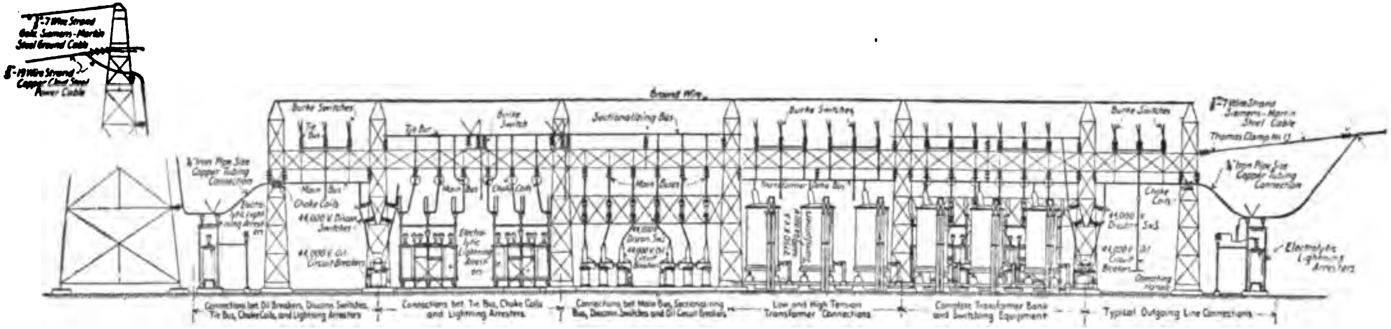

⅝"-7 Wire Strand Galv. Siemens-Martin Steel Ground Cable
⅝"-19 Wire Strand Copper Clad Steel Power Cable
¾" Iron Pipe Size Copper Tubing Connection
Electrolytic Lightning Arresters
Burke Switches
Tie Bus
Main Bus
Choke Coils
44,000 V Discon. Switches
44,000 V Oil Circuit Breakers
Tie Bus
Burke Switch
Main Bus
Choke Coils
Electrolytic Lightning Arresters
Ground Wire
Sectionalizing Bus
Main Buses
44,000 V Discon. Sw.
44,000 V Oil Circuit Breakers
Burke Switches
Transformer Delta Bus
2750 K.V.A. Transformers
Burke Switches
⅝"-7 Wire Strand Siemens-Martin Steel Cable
Thomas Clamp No. 13
¾" Iron Pipe Size Copper Tubing Connection
Choke Coils
44,000 V Discon. Sw.
44,000 V Oil Circuit Breakers
Operating Handle
Electrolytic Lightning Arresters
Connections bet. Oil Breakers, Discon. Switches, Tie Bus, Choke Coils, and Lightning Arresters
Connections bet. Tie Bus, Choke Coils and Lightning Arresters
Connections bet. Main Bus, Sectionalizing Bus, Discon. Switches and Oil Circuit Breakers
Low and High Tension Transformer Connections
Complete Transformer Bank and Switching Equipment
Typical Outgoing Line Connections

Fig. 232.—Outdoor Substation at Cabin Creek Junction Steam Station of Virginia Power Company Showing Arrangement of Apparatus

This substation is just outside a 20,600 kva. steam station which serves coal mines in the New River coal fields of West Virginia, within a radius of about 50 miles. The station circuits are shown in Fig. 219. About 156 miles of 44,000 volt transmission lines and 30 miles of 2,300 distribution lines are operated. Coal costs about $0.95 per ton delivered at the plant.

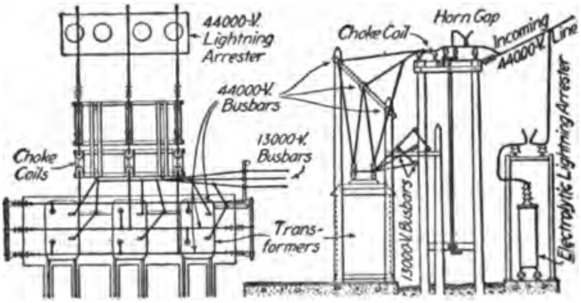


Fig. 233.—Arrangement of 2250 Kva. Outdoor Substation Equipment

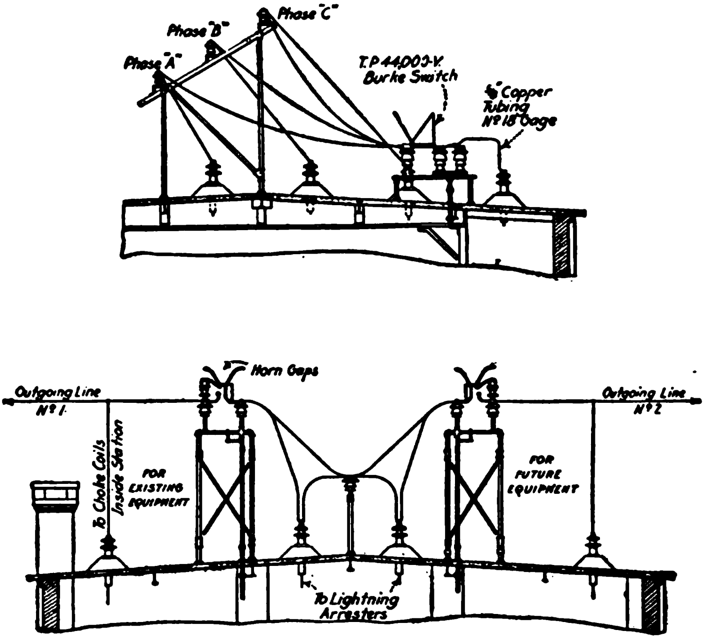


Fig. 234.—Roof Outlets and Circuits for Outgoing Transmission Lines

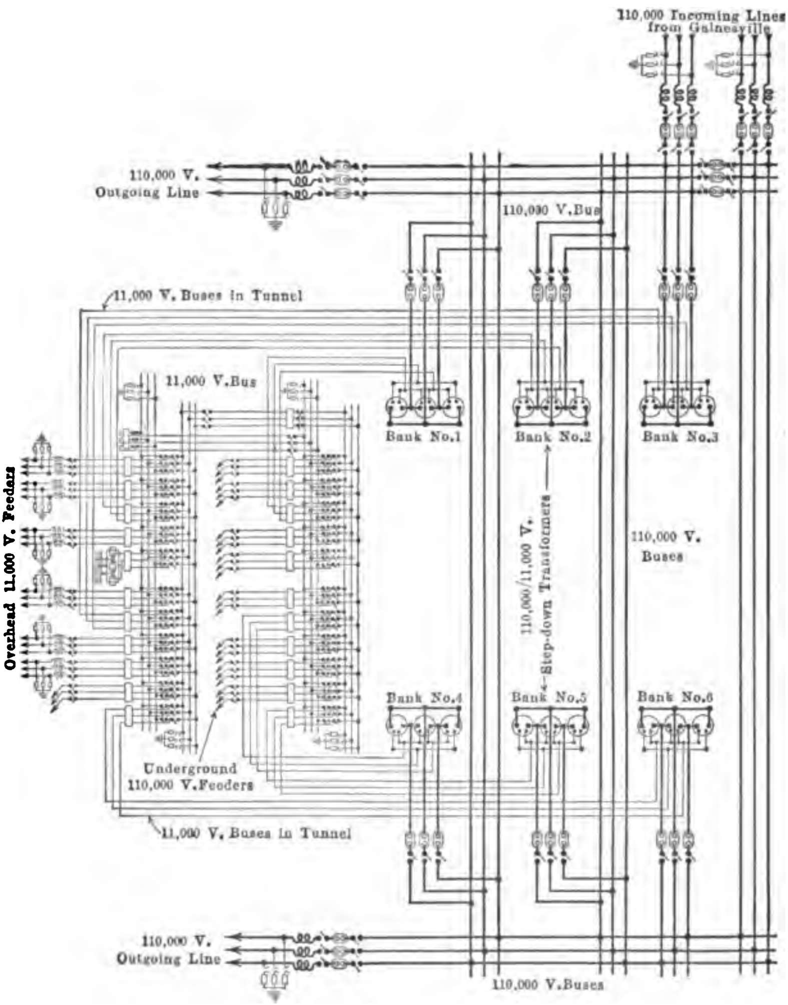

110,000 Incoming Lines from Gainesville
110,000 V. Outgoing Line
110,000 V.Bus
11,000 V. Buses in Tunnel
11,000 V.Bus
Bank No.1
Bank No.2
Bank No.3
Overhead 11,000 V. Feeders
110,000/11,000 V. Step-down Transformers
110,000 V. Buses
Bank No.4
Bank No.5
Bank No.6
Underground 110,000 V.Feeders
11,000 V. Buses in Tunnel
110,000 V. Outgoing Line
110,000 V.Buses

Fig. 235.—Layout of Apparatus and Circuits for Atlanta Substation of Georgia Railway and Power Company Rated at 60,000 Kva. When Constructed in 1913 this was the Largest Outdoor Substation in the World

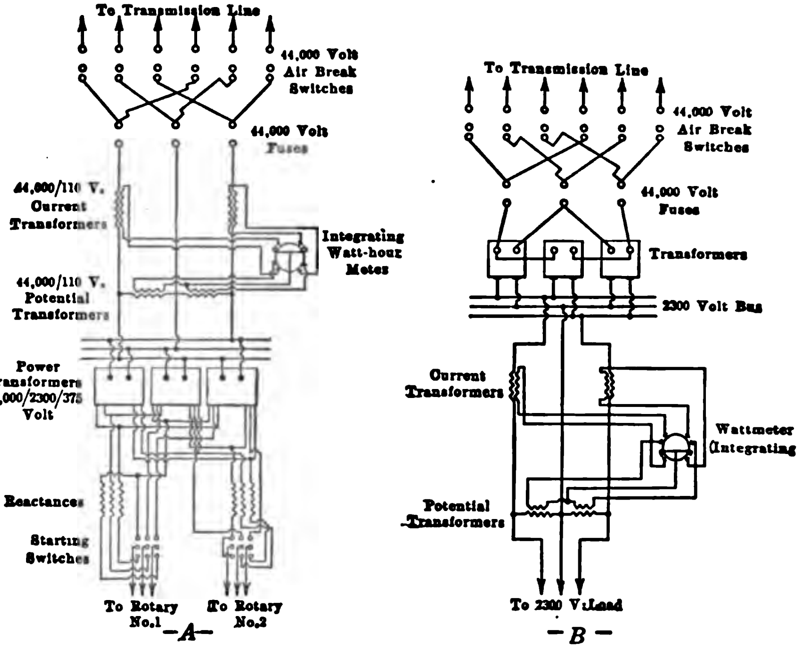


Fig. 236.—Metering Connections used by Virginia Power Company for Small Mine Substations

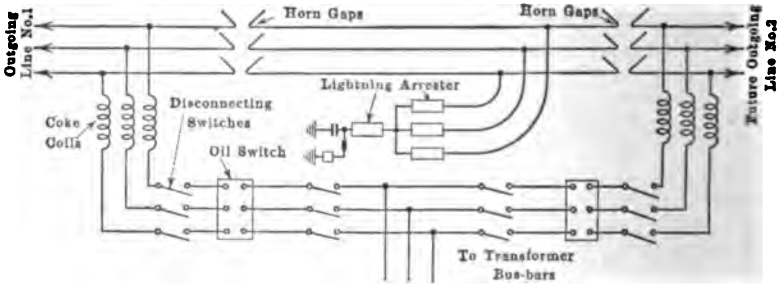


Fig. 237.—Arrangement of Lightning Arresters for a Plurality of Lines

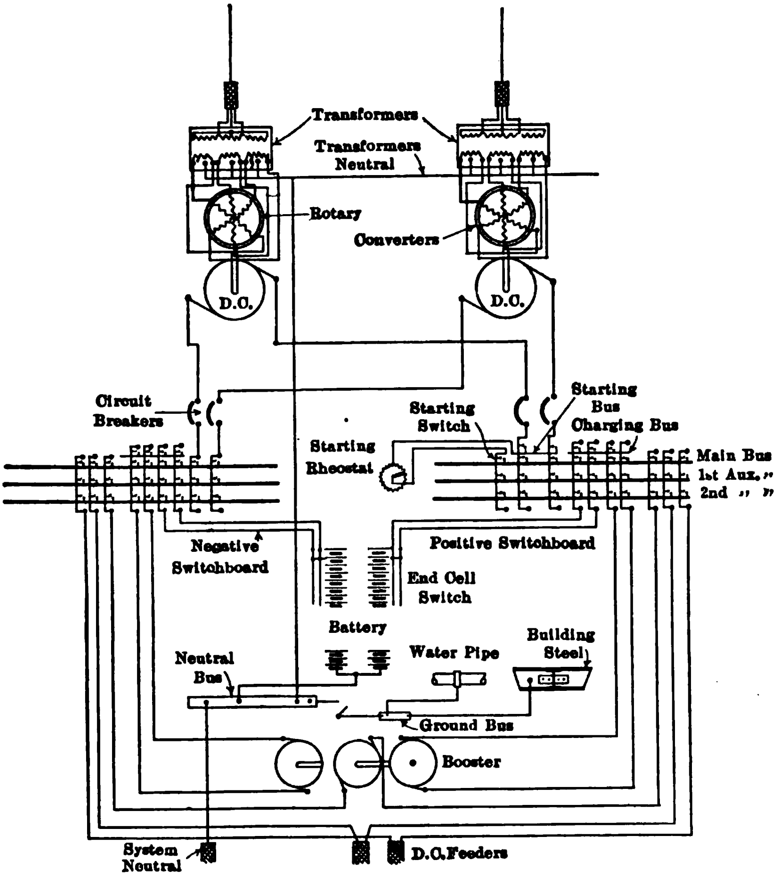
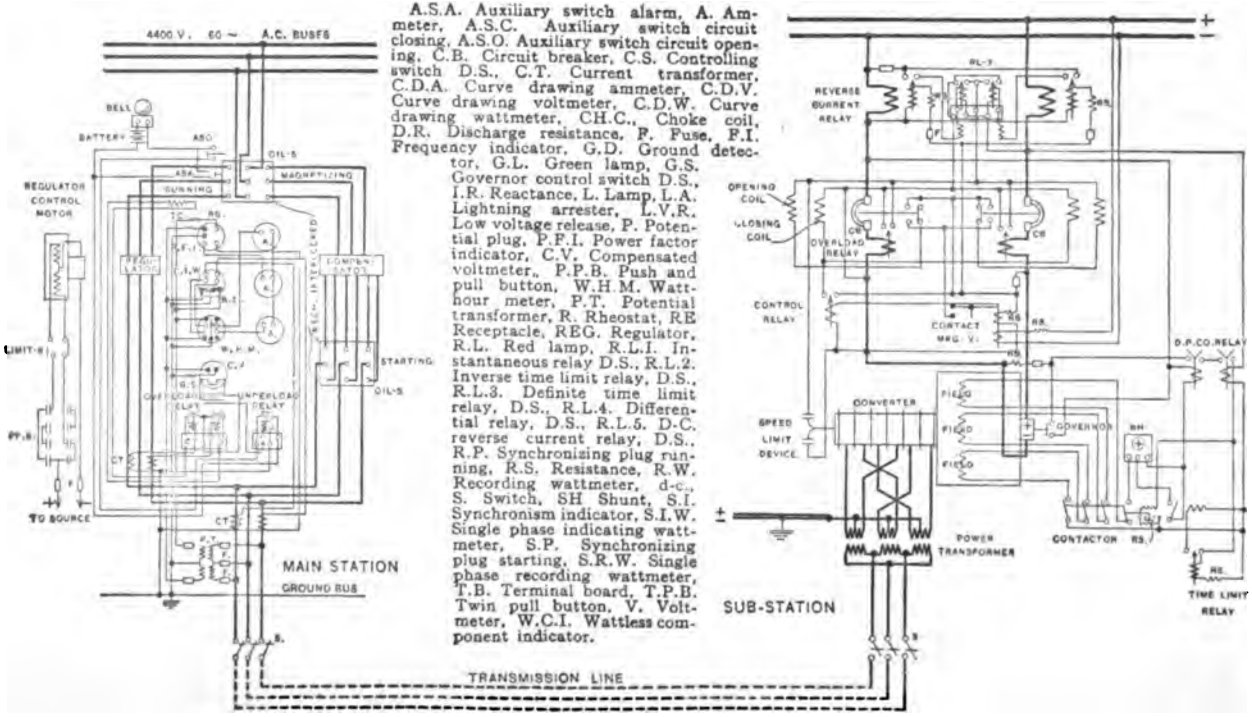


Fig. 238.—An Arrangement of Circuits for Rotary Converters and Booster

This installation is in a theatre district substation of the New York Edison Company. Any converter can be operated from any high tension feeder and any direct current feeder or group of feeders can be connected with any converter.



A.S.A. Auxiliary switch alarm, A. Ammeter, A.S.C. Auxiliary switch circuit closing, A.S.O. Auxiliary switch circuit opening, C.B. Circuit breaker, C.S. Controlling switch D.S., C.T. Current transformer, C.D.A. Curve drawing ammeter, C.D.V. Curve drawing voltmeter, C.D.W. Curve drawing wattmeter, CH.C., Choke coil, D.R. Discharge resistance, F. Fuse, F.I. Frequency indicator, G.D. Ground detector, G.L. Green lamp, G.S. Governor control switch D.S., I.R. Reactance, L. Lamp, L.A. Lightning arrester, L.V.R. Low voltage release, P. Potential plug, P.F.I. Power factor indicator, C.V. Compensated voltmeter,, P.P.B. Push and pull button, W.H.M. Watt-hour meter, P.T. Potential transformer, R. Rheostat, RE Receptacle, REG. Regulator, R.L. Red lamp, R.L.I. Instantaneous relay D.S., R.L.2. Inverse time limit relay, D.S., R.L.3. Definite time limit relay, D.S., R.L.4. Differential relay, D.S., R.L.5. D-C. reverse current relay, D.S., R.P. Synchronizing plug running, R.S. Resistance, R.W. Recording wattmeter, d-c., S. Switch, SH Shunt, S.I. Synchronism indicator, S.I.W. Single phase indicating wattmeter, S.P. Synchronizing plug starting, S.R.W. Single phase recording wattmeter, T.B. Terminal board, T.P.B. Twin pull button, V. Voltmeter, W.C.I. Wattless component indicator.

Fig. 239.—Arrangements of Circuits for an Automatic Substation

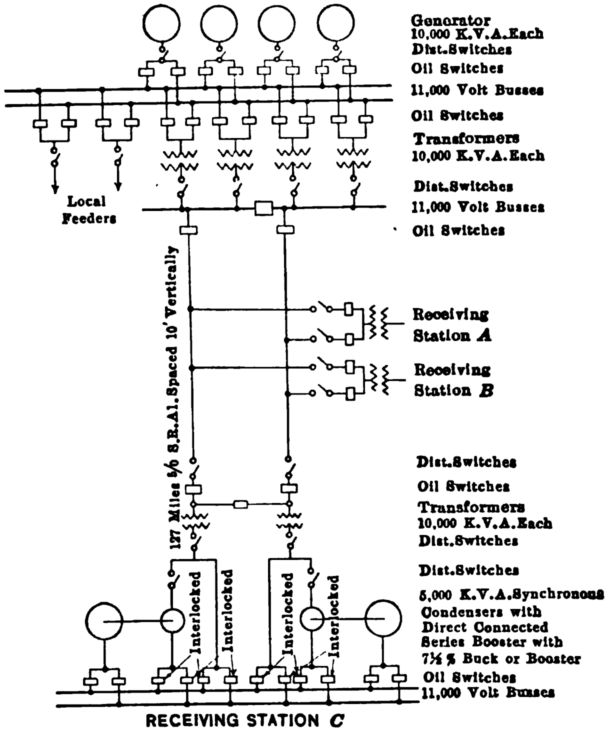


Fig. 240.—Connections Showing Proper Location of Synchronous Condenser and Booster

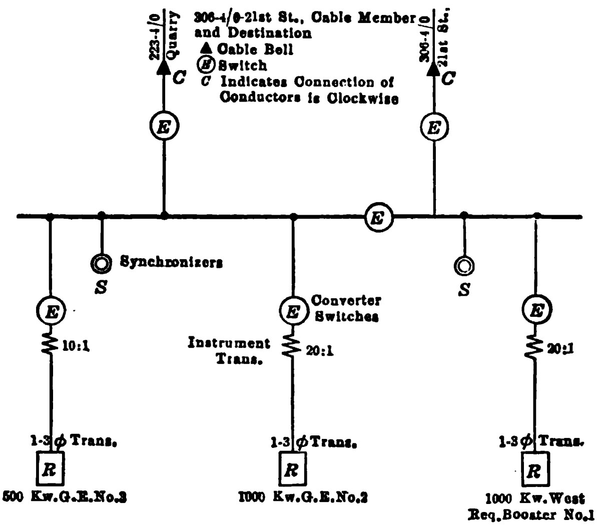


Fig. 241.—Circuits of Small Rotary Converter Substation of Chicago System

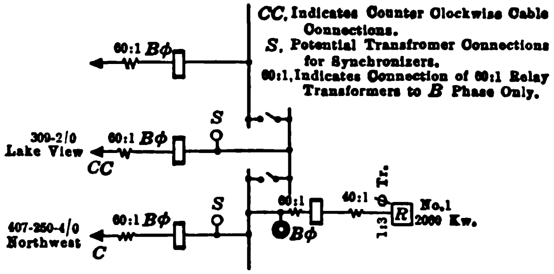

CC, Indicates Counter Clockwise Cable Connections.
S, Potential Transfromer Connections for Synchronizers.
60:1, Indicates Connection of 60:1 Relay Transformers to B Phase Only.
60:1 Bϕ
S
309-2/0 Lake View
60:1 Bϕ
CC
S
407-250-4/0 Northwest
60:1 Bϕ
C
60:1
Bϕ
40:1
1:3 Tr.
R
No. 1 2000 Kw.

Fig. 242.—Electric Railway Substation Showing Transfer Bus Arrangement

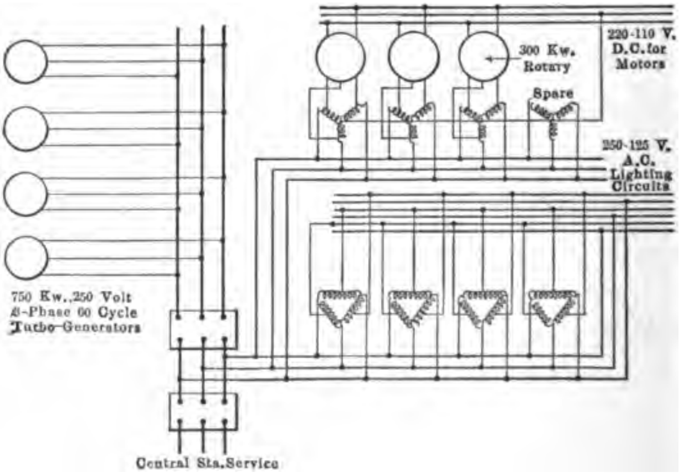

300 Kw. Rotary
Spare
220-110 V. D.C. for Motors
250-125 V. A.C. Lighting Circuits
750 Kw., 250 Volt 3-Phase 60 Cycle Turbo-Generators
Central Sta. Service

Fig. 243.—Arrangements for a Give and Take Power Agreement with an Isolated Plant

Service is furnished to an office building during winter from an isolated plant and in summer energy is purchased. Plant is operated by Light and Development Company of St. Louis, Mo.

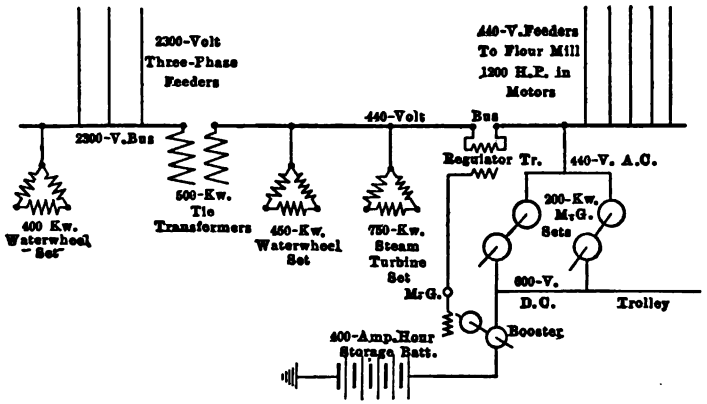


Fig. 244.—System of Connections for a Generating Station Supplying both Alternating and Direct Current Energy to Industrial Plants and Railways from Steam and Water Power Units Arranged to Operate in Parallel

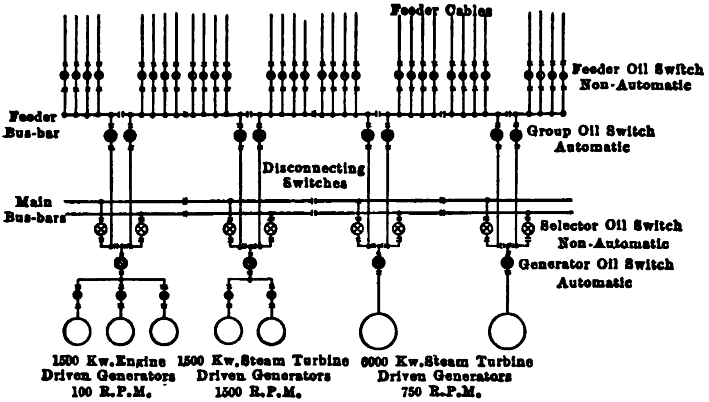


Fig. 245.—System of Connections for a 9,000 Kw. Generating Station

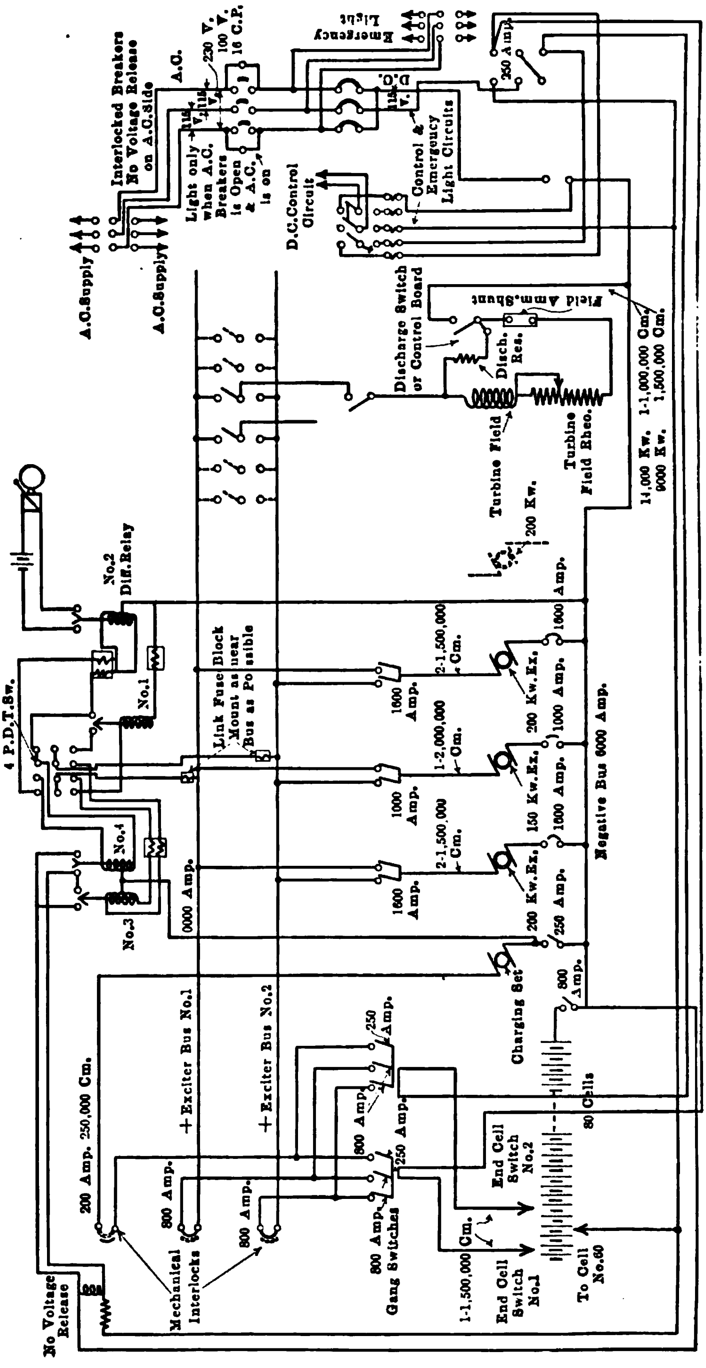


Fig. 246.—System of Connections for a Large Exciter Bus and Auxiliary Battery Showing Alternating Current Supply and System of Protection

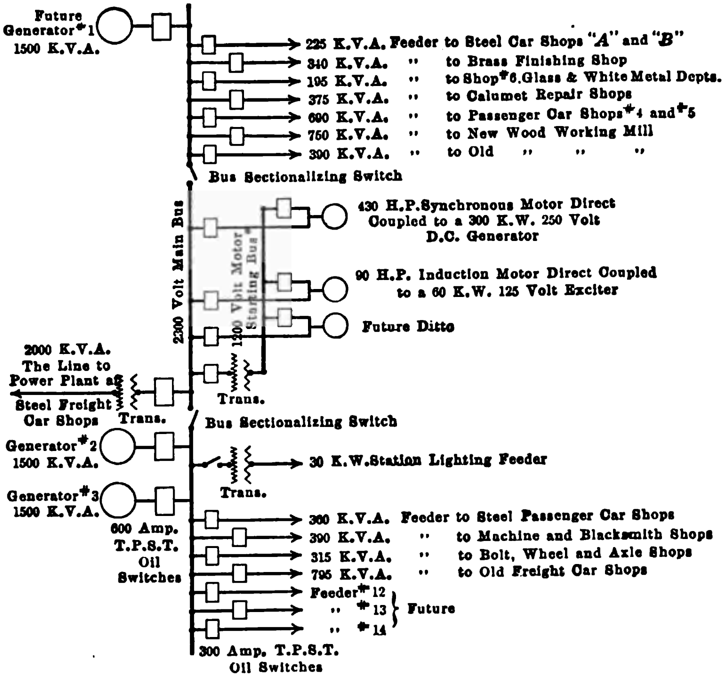

Future Generator #1 1500 K.V.A.
225 K.V.A. Feeder to Steel Car Shops "A" and "B"
340 K.V.A. " to Brass Finishing Shop
195 K.V.A. " to Shop #6. Glass & White Metal Depts.
375 K.V.A. " to Calumet Repair Shops
690 K.V.A. " to Passenger Car Shops #4 and #5
750 K.V.A. " to New Wood Working Mill
300 K.V.A. " to Old " " "
Bus Sectionalizing Switch
2300 Volt Main Bus
1200 Volt Motor Starting Bus
430 H.P. Synchronous Motor Direct Coupled to a 300 K.W. 250 Volt D.C. Generator
90 H.P. Induction Motor Direct Coupled to a 60 K.W. 125 Volt Exciter
Future Ditto
2000 K.V.A. The Line to Power Plant at Steel Freight Car Shops
Trans.
Trans.
Bus Sectionalizing Switch
Generator #2 1500 K.V.A.
30 K.W. Station Lighting Feeder
Trans.
Generator #3 1500 K.V.A.
600 Amp. T.P.S.T. Oil Switches
300 K.V.A. Feeder to Steel Passenger Car Shops
390 K.V.A. " to Machine and Blacksmith Shops
315 K.V.A. " to Bolt, Wheel and Axle Shops
795 K.V.A. " to Old Freight Car Shops
Feeder #12
" #13
" #14
Future
300 Amp. T.P.S.T. Oil Switches

Fig. 247.—System of Connections in a Generating Station Supplying Energy to a Large Industrial Plant

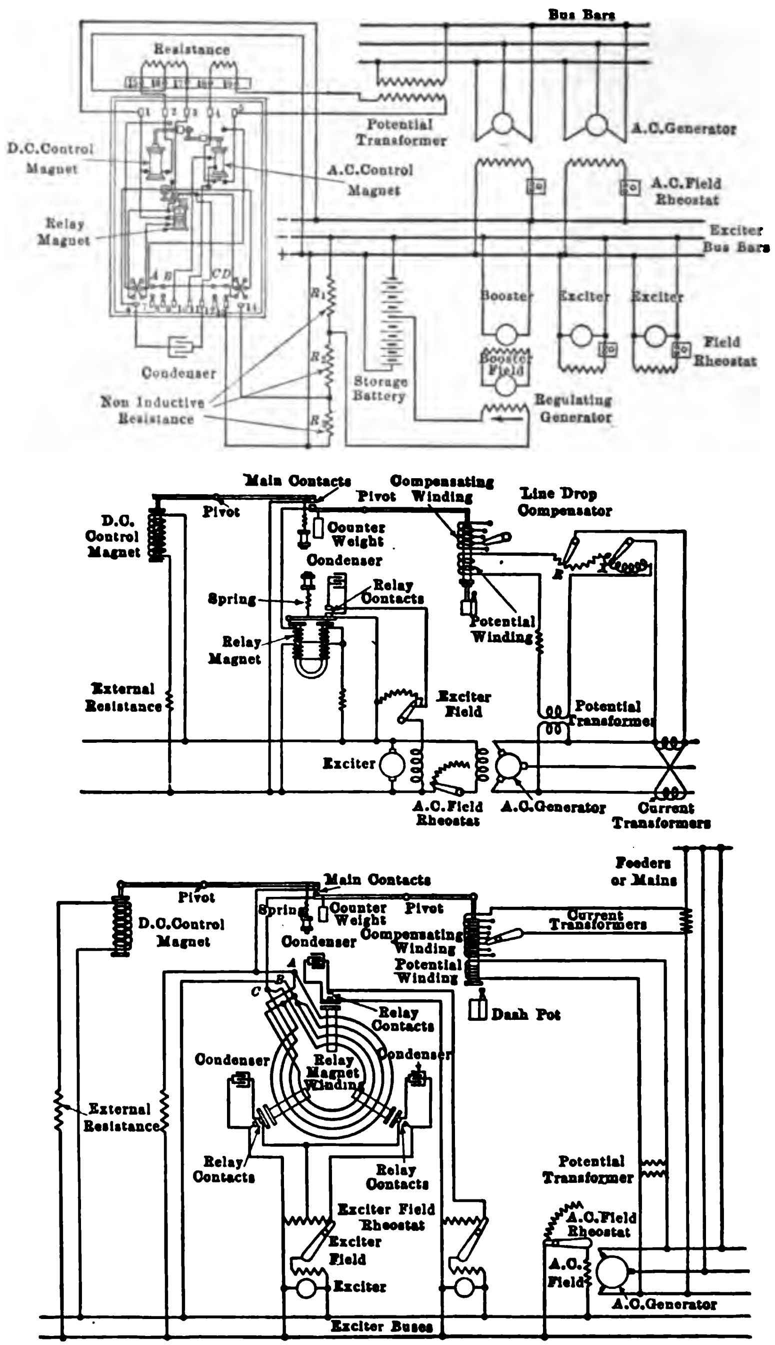


Fig. 248.—System of Connections for Exciting Alternators

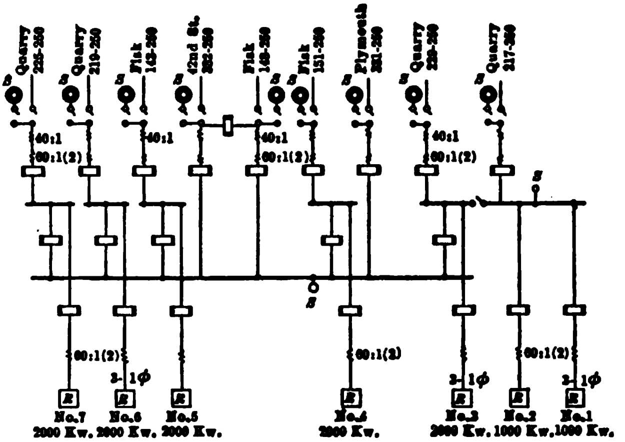


Fig. 249.—Elaborate Layout of Circuits for a Large Substation

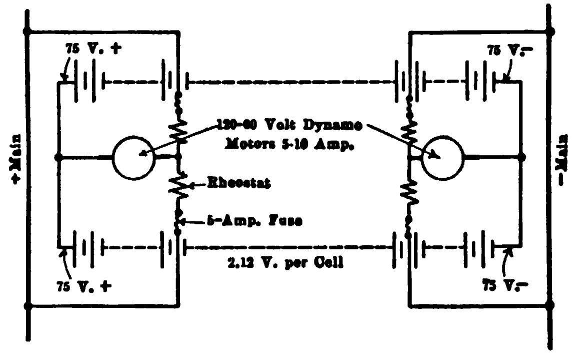


Fig. 250.—An Effecting Scheme for Charging End Cells Used on a System of Auxiliary Batteries for Exciting Alternating Current Generators

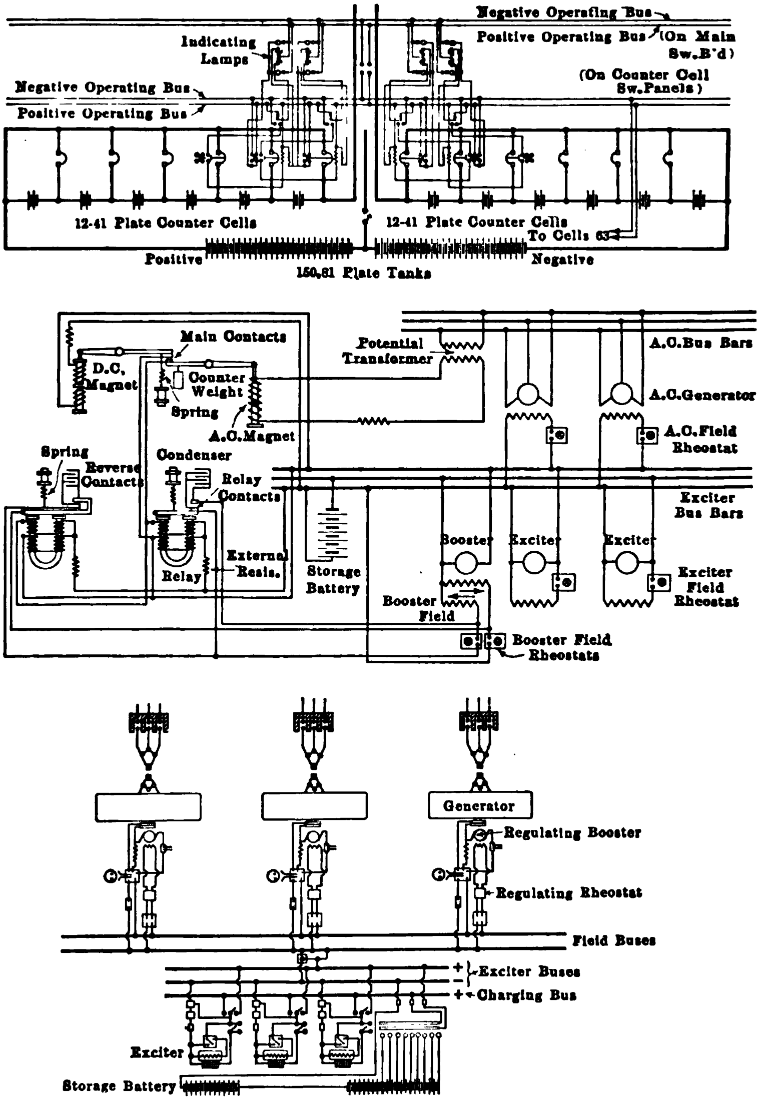


Fig. 251.—Exciter and Battery Schemes for Exciting Alternating Current Generators

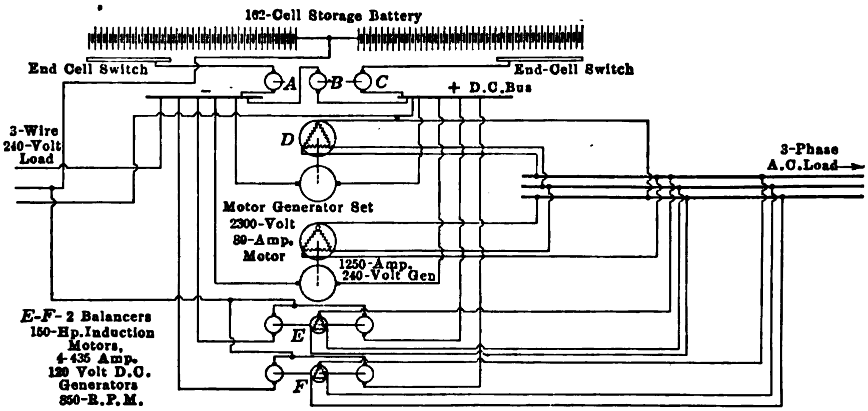


Fig. 252.—Arrangement of Battery Circuits to Serve Both Alternating and Direct Current Distribution Systems

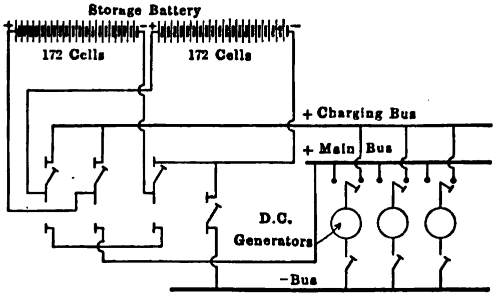


Fig. 253.—Switching Arrangements for Charging Each Half of a Battery in Parallel

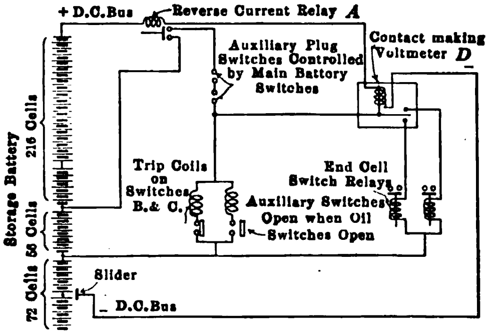

+ D.C.Bus
Reverse Current Relay A
Auxiliary Plug Switches Controlled by Main Battery Switches
Contact making Voltmeter D
Storage Battery
216 Cells
56 Cells
72 Cells
Trip Coils on Switches B.& C.
End Cell Switch Relays
Auxiliary Switches Open when Oil Switches Open
Slider
- D.C.Bus

Fig. 254.—An Arrangement to Permit a Reserve Battery to Carry an Alternating Current Load in Substation of Boston Edison Company

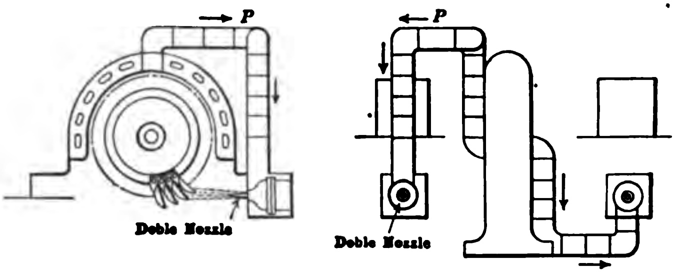


Fig. 255.—Method of Ventilating to Increase Rating of Water Wheel Generators

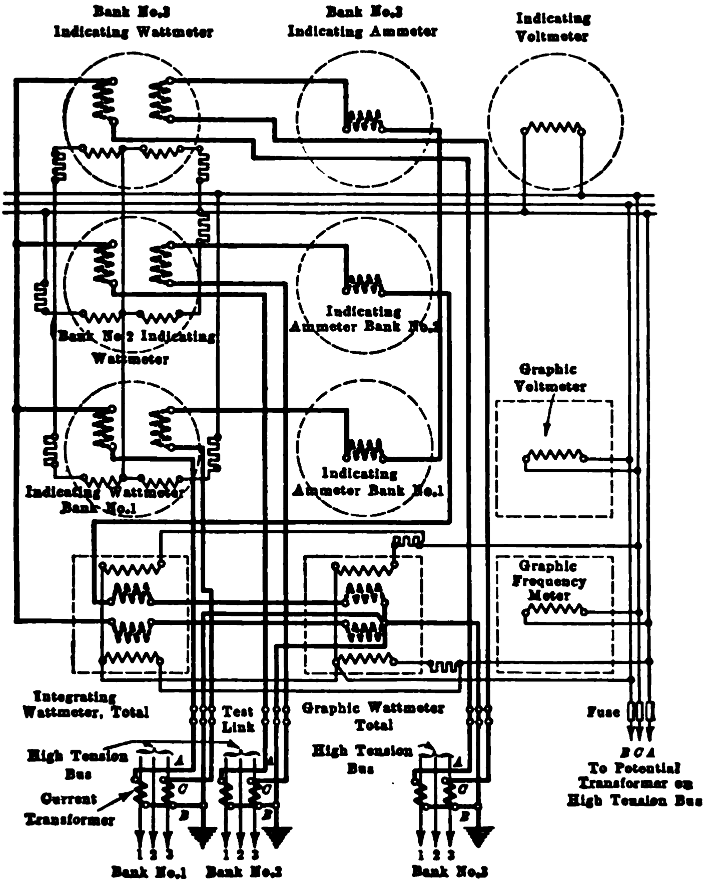

Bank No.3 Indicating Wattmeter
Bank No.3 Indicating Ammeter
Indicating Voltmeter
Bank No 2 Indicating Wattmeter
Indicating Ammeter Bank No.2
Graphic Voltmeter
Indicating Wattmeter Bank No.1
Indicating Ammeter Bank No.1
Graphic Frequency Meter
Integrating Wattmeter, Total
Test Link
Graphic Wattmeter Total
Fuse
High Tension Bus
Current Transformer
A
C
B
High Tension Bus
B C A
To Potential Transformer on High Tension Bus
1 2 3
Bank No.1
1 2 3
Bank No.2
1 2 3
Bank No.3

Fig. 256.—Connections for Minimizing Series Transformers

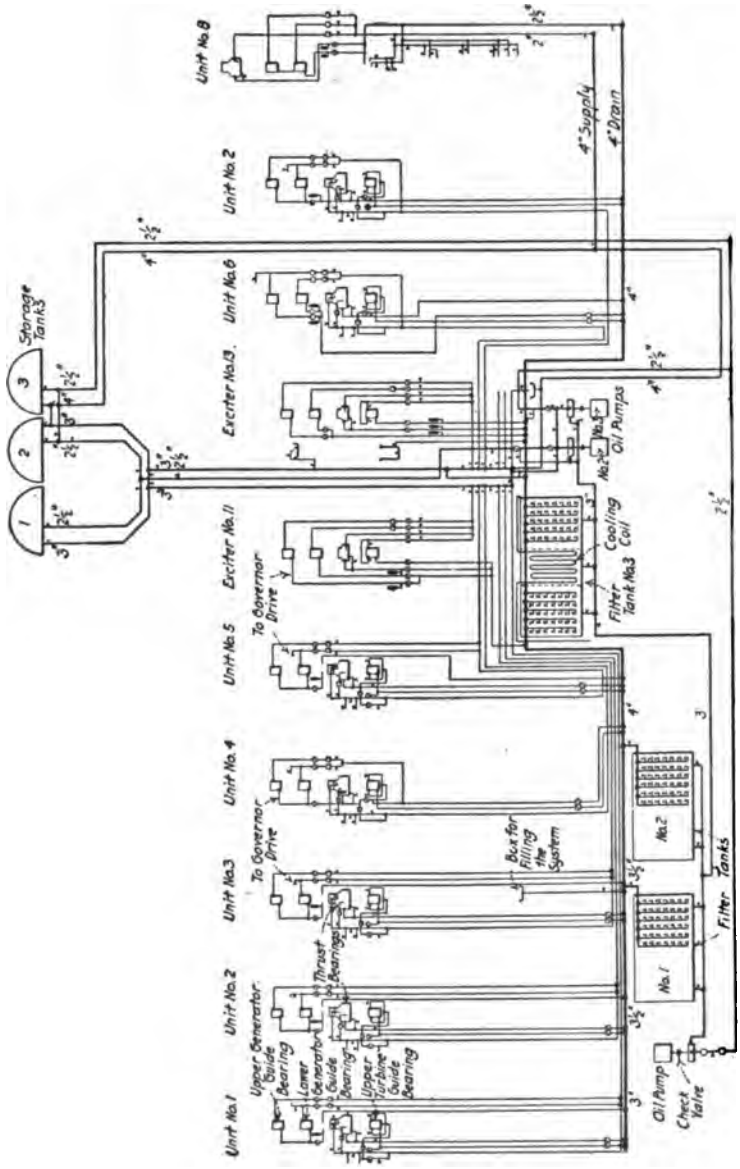


Fig. 257.—Oiling System for Water Wheel Units in Holtwood Station of Pennsylvania Water and Power Company

CONSTRUCTION RULES FROM NATIONAL ELECTRICAL SAFETY CODE

The following information has been abstracted from sections of the "National Electrical Safety Code" (Second Edition, November 15, 1916) dealing with the installation and maintenance of overhead lines. The rules as presented have been formulated by the Bureau of Standards, U.S. Department of Commerce, for incorporation in the Code which proposes national standards for the safe construction and installation of electrical equipment in stations, of electrical transmission, distribution and signal lines and of the electrical utilization equipment of factories and the like. Only those rules are given here which deal with overhead lines and embody recommendations and considerations that are important to reliable and safe construction. For a complete version of all rules the code itself should be consulted.

In the following rules different grades of overhead line construction are referred to and designated as A, B, and C. The conditions determining each grade of construction are defined in paragraphs Nos. 211 to 219 which follow and have largely to do with the various conditions of hazard involved.

Grades of Overhead Construction

211. Supply Lines Crossing Over Railways. Supply lines carried over railways, operated by steam, electric, or other motive power, except as provided in rule 212 below, shall conform to the construction requirements of grade A.

212. Supply Lines Crossing Over Unimportant Railways. (a) Supply lines carried over sidings not exceeding four tracks, or over spurs, or over branches or other unimportant railways operated by steam, electric, or other motive power, shall, with the exception noted in (b) below, conform to the construction requirements of grade B.

Unimportant railways generally are those having not more than a single parallel signal circuit. Single circuits carried over a different right of way for part of their route, but concerned in the operation of the railway line, are included as parallel signal circuits, within the intent of this paragraph.

(b) Supply lines carried over street railways, which are on traveled portions of highways, need conform only to the general requirements of sections 22 and 23 for supply lines other than those of grades A, B, and C and to the construction requirements of rules 217, 218 and 219 where they apply, the trolley contact conductor being considered for the purposes of this rule as a supply conductor of equal voltage.

213. Signal Lines Crossing Over Railways. (a) Telephone, telegraph, and other signal lines carried over railways operated by steam, electric, or other motive power shall, with the exceptions noted below, conform to the construction requirements of grade D, as given in section 28.

(b) Signal lines carried over sidings not exceeding four tracks, or over spurs or over branches or other unimportant railways operated by steam, electric, or other motive power, shall conform, except as noted below, to the construction requirements of grade E, as given in section 28.

(c) Signal lines carried over street railways not having overhead trolley contact conductors exceeding 750 volts, where such street railways are located on traveled portions of highways, need conform only to the general construction requirements of section 28 for signal lines in these situations.

(d) Signal lines carried over electric railways having overhead trolley contact conductors above 750 volts shall conform to the construction requirements of grades A, B or C, according as the conditions listed in rules 214, 215, or 216 apply.

(e) Signal lines which have assumed the character of supply lines shall, where crossing over railways, conform to the construction requirements of rules 211 or 212, according to the character of the railway concerned.

214. HIGH VOLTAGE SUPPLY LINES IN CROSSING, CONFLICTS, AND COMMON USE OF POLES WITH SIGNAL LINES. (a) Constant-potential alternating-current supply lines of over 7500 volts, or constant-current circuits exceeding 10 amperes, or direct-current grounded trolley circuits of over 750 volts, where at higher levels and crossing over or conflicting or on common poles with telephone, telegraph, or other signal lines shall conform to the construction requirements of grade A, except as noted below:

(1) It is not intended that this requirement shall apply to supply lines at higher levels than signal lines, where over individual twisted pair drop wires only, or where over other unimportant circuits only, if equally effective protection is secured by other methods of construction.

(2) Where the signal line is at a lower level than the supply line and carries not more than four wires used mainly for local exchange service, or carries only subscribers' loops, or carries not more than two unimportant commercial telegraph wires, grade B may be used for the supply line.

(b) Signal lines, carried at higher levels than the supply lines listed in (a) above, in crossings, conflicts, or common use of poles, shall be of the grade of construction required in (a) for the supply lines.

215. MEDIUM VOLTAGE SUPPLY LINES IN CROSSINGS, CONFLICTS, AND COMMON USE OF POLES WITH SIGNAL LINES. (a) Constant-potential alternating-current supply lines of between 5000 and 7500 volts, or constant-current circuits of between 7.5 and 10 amperes, where at higher levels and crossing over or in conflicts or on common poles with the telephone, telegraph, or other signal lines shall conform to the construction requirements of grade B, except as noted below.

It is not intended that this requirement shall apply to supply lines at higher levels than signal lines where the latter are individual twisted pair drop wires only, or where over other unimportant circuits only if equally effective protection is secured by other methods of construction.

(b) Signal lines carried at higher levels than the supply lines listed in (a) above in crossings, conflicts, or common use of poles shall be of the grade of construction required in (a) for the supply lines.

216. LOW VOLTAGE SUPPLY LINES IN CROSSINGS, CONFLICTS, AND COMMON USE OF POLES WITH SIGNAL LINES. (a) Constant-potential alternating-current supply lines between 750 and 5000 volts, and constant-current circuits not exceeding 7.5 amperes, in urban districts, where at higher levels and crossing over or conflicting with or on common poles with signal lines shall conform to the construction requirements of grade C, except as noted below.

It is not intended that this requirement shall apply to supply lines at higher levels than signal lines, where over individual twisted pair drop wires only, or where over other unimportant circuits only, if equally effective protection is secured by other methods of construction.

(b) Signal lines carried at higher levels than the supply lines listed in (a) above, in crossings, conflicts, or common use of poles shall be of the grade of construction required in (a) for the supply lines, except as smaller wire sizes are permitted by rule 221.

217. SUPPLY LINES ABOVE 7500 VOLTS IN URBAN DISTRICTS. Constant-potential supply lines and constant-current circuits over 7500 volts in urban districts, where alone (except on fenced rights of way), or where crossing over, or in conflicts, or on common poles, with other supply lines or constant-current circuits, shall conform to the construction requirements of grade B.

218. SUPPLY LINES OF 750 TO 7500 VOLTS IN URBAN DISTRICTS. Constant-potential supply lines and constant-current circuits between 750 and 7500 volts in urban districts where alone (except on fenced rights of way), or where at higher levels and crossing over,

or in conflicts, or on common poles with supply lines or with constant-current circuits under 7500 volts, shall conform to the construction requirements of grade C. If the other circuits concerned exceed 7500 volts grade B is required.

219. SUPPLY LINES ABOVE 7500 VOLTS IN RURAL DISTRICTS. (a) Supply lines or constant-current lines above 7500 volts in rural districts at higher levels and crossing over, or in conflicts, or on common poles with supply lines not exceeding 750 volts shall conform to the construction requirements of grade C.

(b) Supply lines above 7500 volts are exempted from this requirement if crossing over or conflicting with only service connections from supply lines.

(c) Supply lines below 750 volts in rural districts at higher levels and crossing over, or in conflicts with, or on common poles with lines exceeding 7500 volts shall conform to the construction requirements of grade C.

222. LOADS ASSUMED IN DETERMINING STRESSES IN CONDUCTORS. (a) In computing the longitudinal stresses upon conductors and their supports, and the sags corresponding in given limiting stresses in conductors, the loading shall be assumed to be one of the following, according to climatic conditions of the locality concerned. Lightning protection wires are to be regarded, in respect to these mechanical requirements, as supply conductors.

(*1*) *Heavy Loading.*—The resultant loading of 0° F., due to the weight of the conductor plus the added weight of a layer of ice one-half inch in radial thickness, combined with a transverse horizontal wind pressure of 8 pounds per square foot on the projected diameter of the ice-covered conductor, shall be called heavy loading.

(*2*) *Medium Loading.*—The resultant loading at 15° F., due to wind and the weight of the conductor and ice, equal to two-thirds that specified in (1) above, but in no case less than 25 per cent. in excess of the weight of the conductor, shall be called medium loading.

Only with copper conductors of 400,000 circular mils or larger size or with very large conductors of other material is the resultant loading less than 25 per cent in excess of the conductor weight.

(*3*) *Light Loading.*—The resultant loading, at 30° F., due to wind and the weight of the conductor, equal to two-thirds that specified in (2) above of four-ninths that of (1), but in no case less than 25 per cent. in excess of the weight of the conductor, shall be called light loading. (See Table 22 for resulting loads on conductors.)

Only with copper conductors of No. 000 or larger size or with very large conductors of other material is the resultant loading less than 25 per cent. in excess of the conductor weight.

(b) Three districts have been outlined in which heavy, medium, and light loading, respectively, are considered to be justified by weather reports as to wind and ice and by local experience of the utilities using overhead lines. A map of the United States showing the territory falling into each class of loading is given in Fig. 258 (Appendix A of Code). This classification is the same as that for the calculation of transverse pressures on the supporting structures (rule 230) and is to be determined or modified as there indicated.

Sec. 23. Strength of Poles, Towers, and Other Line Supports

230. BASIS FOR CALCULATION OF TRANSVERSE LOADS UPON POLES AND TOWERS. (a) In computing the stresses upon poles and towers for which grades of construction A, B, or C are required the assumed horizontal wind pressures at right angles to the direction of the line, upon the poles, towers, and conductors, shall be taken in regions of heavy loading for cylindrical surfaces, as 12 pounds per square foot of projected area for grade A, 7 pounds for grade B, and 4 pounds for grade C, the pressure being computed

for the poles and towers without ice covering, while conductors are assumed to be covered with a layer of ice one-half inch in radical thickness.

Lightning protection wires and trolley contact conductors are included in computing transverse stresses.

(b) In regions of medium loading the transverse pressure shall be taken as two-thirds that for heavy loading districts and in regions of light loading the transverse pressure shall be assumed to be two-thirds that for medium loading districts, that is, four-ninths of that for heavy loading districts.

(c) A map of the United States showing the territory falling into each class of loading is given in Fig. 258 (Appendix A of Code). (See also rule 222b.) The localities in the different groups are classed according to the relative prevalence of high wind velocity and thickness of ice which accumulates on wires, light loading being for places where no ice of appreciable thickness ever accumulates on wire.

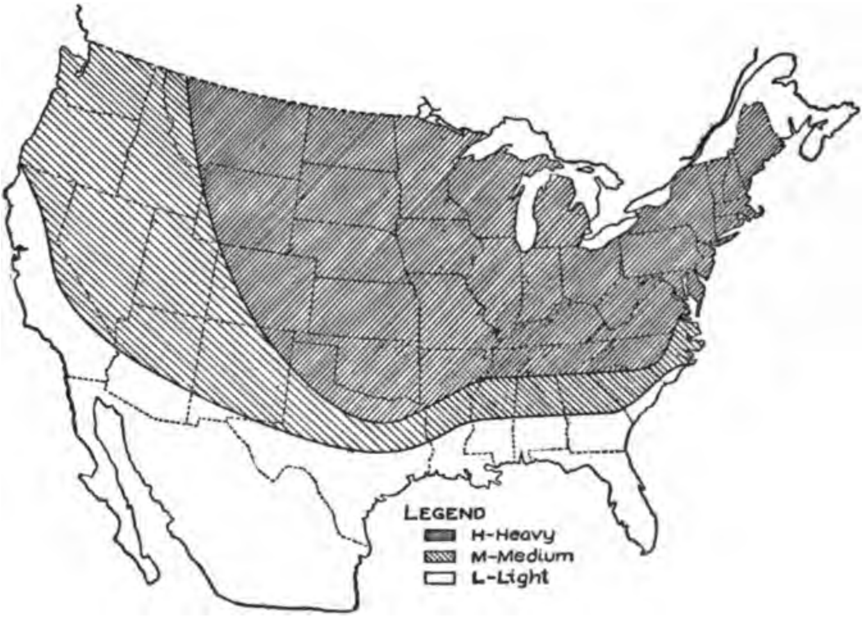


Fig. 258.—Territorial Division of the United States with Respect to Loading on Electric Transmission Lines

Where high-wind velocities are frequent in a given place the loading for that place may be classed as heavy even though ice does not accumulate to any greater extent than at some other place having less severe winds which has been classed as a medium loading district.

(d) In the absence of any action by the administrative authority fixing the loadings for any given jurisdiction the classification of loadings shown on the map Fig. 258 (Appendix A of Code) shall be considered to apply unless the party or parties responsible for the lines concerned assume some modification of the same, based upon local experience or weather records, or both. These modifications shall be subject to review by the administrative authority.

232. Calculation of Loads upon Line Supports. (a) The loads upon poles, towers, and crossarms shall be taken as the following:

(*1*) *Vertical.*—Their own weight, plus the weight of the ice-covered conductors supported. The thickness of ice shall be taken as ½ inch in regions of heavy loading, ¼ inch in regions of medium loading, and no ice shall be considered in regions of light loading. (See Table 24 for vertical loads on conductors.)

(2) *Horizontal.*—The assumed transverse pressures against their own surfaces (projected area when cylindrical) and against the ice-covered conductors, as specified in rule 230 above; heavy, medium, or light, according to the locality. (See Table 23 for transverse loads on conductors.)

(b) The calculated loads upon poles, towers, and crossarms shall be based upon the average span length where longer and shorter spans are interspersed except for spans which are over 25 per cent. in excess of the average, in which case the actual span lengths shall be used. In the case of crossings the actual length of span shall be used.

(c) In the calculation of all stresses no allowance shall be made for deformation, deflection, or displacement of any part of the supporting structures. (See also rule 220.)

(d) For flat surfaces the assumed unit pressure (see rule 230) shall be increased by 60 per cent. Where latticed structures are concerned, the actual exposed areas of one lateral face shall be increased by 50 per cent. to allow for the pressure on the opposite face. If, however, this method of computing pressure on latticed structures indicates a greater total pressure than would occur on a solid structure of the same outside dimensions, the latter shall be taken as the limit.

233. SPECIAL TRANSVERSE STRENGTH REQUIREMENTS. (a) In the case of structures of grades A, B, or C construction where because of very heavy or numerous conductors or abnormally long spans the transverse strength requirements of this section can not be met except by the use of side guys or special structures, and it is physically impracticable to employ side guys, the transverse strength requirements may be met by side guying the line at each side of and as near as practicable to the crossing or other transversely weak structure, and with a distance between such side-guyed structures of not over 800 feet, provided·

(1) The side-guyed structures for each such section of 800 feet or less shall be constructed to withstand the calculated transverse load due to wind on the supports and ice-covered conductors, on the entire section between the side-guyed structures.

(2) The pole or tower structures so side guyed shall be rigid or head guyed away from the transversely weak section and have sufficient strength to withstand under the condition of loading prescribed in this section a load equivalent to the combined pull of all the conductors supported.

(3) The line between such side-guyed structures shall be substantially in a straight line and the average length of span between the side-guyed structures shall not be in excess of 150 feet.

(b) The crossarms, insulator pins, and conductor fastenings connected to the structures at each end of the transversely weak section shall be constructed to withstand, under the conditions of loading prescribed in rule 222, an unbalanced load equivalent to the combined pull in the direction of the transversely weak section of all the conductors supported up to 10,000 pounds, plus one-half the excess for grade A, or plus one-fourth the excess for grade B.

If the tension in any conductor does not exceed 1000 pounds, the necessary strength will usually be provided by the use of single wood pins and if the tension does not exceed 2000 pounds by the use of double wood pins provided the lever arm of the pin does not exceed 3.5 inches.

(c) Except as modified in this rule the construction of the transversely weak section of the line shall be in accordance with the requirements for the grade of construction concerned.

234. STRENGTH OF STEEL POLES AND TOWERS AND OTHER METAL SUPPORTS. (a) Steel supports, steel towers, and metal poles, together with their foundations, and guys

when used, shall be so designed and constructed as to withstand the stresses due to the loads assumed in rule 230a above. Under these loads the calculated stresses in the steel members and in the guys shall not exceed the values given below in (f), which are intended to be limiting unit stresses, beyond which the structure as a whole would be liable to failure.

(b) The use of guys to obtain compliances with these requirements is regarded as generally undesirable. When guys are necessarily used, the steel supports or towers shall be regarded as taking all of the stress in the direction in which the guy acts, up to their safe working load, and the guys shall have sufficient strength to take the remainder of the assumed maximum stress, unless capable of considerable deflection.

(c) Steel towers, when carrying no conductors, shall have a minimum strength sufficient to withstand a transverse pressure double that designated for grade A construction.

(d) Steel towers or poles should preferably be placed on concrete or other suitable foundations extending above the ground line. If, however, the steel is set in earth, it shall be suitably protected against injurious corrosion at and below the ground line.

Since in many localities the soil and climatic conditions are such as to alter the strength of foundations considerably from time to time, there should usually be provided a considerable margin of strength in foundations above that which (by calculation) will just withstand the stresses under the assumption of average conditions of climate and soil.

(e) Unless sample structures are tested, or similar structures have been tested, to assure the compliance of structures in any line with these requirements, it is recommended that structures be designed to have a computed strength at least 10 per cent. greater than that required by the rule.

(f) When steel supports or towers are used which are not capable of withstanding practically as great a stress longitudinally as transversely anchor towers shall be placed, at intervals not greater than 10 spans, which shall be able to withstand the combined longitudinal tension of all conductors up to 10,000 pounds plus one-half the excess above 10,000 pounds.

(g) The allowable unit stresses of steel shall be taken as follows:

STRUCTURAL STEEL:	
Tension	27,000 pounds per square inch.
Shear	24,000 pounds per square inch.
Compression	$27{,}000-\frac{L}{r}$.
BOLTS, RIVETS, PINS:	
Shear	24,000 pounds per square inch.
Bearing	48,000 pounds per square inch.
Bending	36,000 pounds per square inch.

These values are for structural steel having an ultimate tensile strength between 55,000 and 65,000 pounds per square inch and a yield point not less than 50 per cent. of the ultimate strength.

(h) Steel poles or towers of grades A, B, and C shall have no less thickness of metal in members than the following:

Legs, galvanized, 5/16 inch; other members, 1/8 inch.

Legs, painted, 1/4 inch, other members, 1/4 inch.

Such steel poles or towers, including footings, shall be so constructed that all parts are accessible for inspection, cleaning, and painting, and that pockets are not formed in which water can collect. The ratio of *L*, the unsupported length of a compression member, to r, the least radius of gyration of the member, should generally not be greater than 150 for legs and 200 for other members having figured stresses.

The straight formula for the allowable stress automatically limits the stresses in steel members to safe values even though the ratio L/r, is greater than the values given above. In other words for larger values of L/r, due to increasing L, the value of the stress is reduced so much that no hazard can result.

(i) *Protective Covering or Treatment.*—All iron or steel poles, towers, or supporting structures, and all hardware, including bolts, washers, guys, anchor rods, and similar parts of material subject to injurious corrosion under the prevailing conditions, shall be protected by galvanizing, painting, or other treatment, which will effectively retard corrosion.

242. REQUIRED LINE-CONDUCTOR CLEARANCES AND SEPARATIONS AT THE SUPPORTS. (a) *Further Requirements for Line-Conductor Separations According to the Sags Concerned.*—The separation, at the supports, of line conductors of the same or different circuits of grades A, B, C, D, or E, shall in no case be less than the values given by the following formulæ, in which S is the apparent sag, in feet, of the conductor having the greater sag if they are at the same level (the same crossarm):

Conductor separations in inches: For sizes below No. 2 = 0.2 inch per kv. $+12\sqrt{S-2}$; for sizes No. 2 and larger = 0.2 inch per kv. $+7\sqrt{S}$.

The separation, at the supports, of line conductors at different levels (different crossarms) shall be determined by these same formulæ.

(b) *Further Requirements for Line-Conductor Separations and Clearances at the Supports if Suspension Insulators are Used.*—(1) Where suspension insulators are used and are not restrained from movement, the values of conductor separation by Table 4 (not given here) or by (a) shall be increased by one-half the length of the suspension insulator string.

(2) Where suspension insulators are used and are not restrained from movement, the conductor clearances from surfaces of supports, from span or guy wires, or from vertical or lateral conductors shall be such that the values of clearances required by Table 3 (not given here) will be maintained with an insulator swing of 45° from the vertical position.

254. INSULATORS. (a) Insulators for operation on supply lines of grades A and B construction at voltages exceeding 7500 shall be of porcelain or other material which will give equally good results in respect to mechanical and electrical performance and durability and shall be marked by the makers with a classification number and maker's name or trade-mark, the marks being so applied as not to reduce the electrical or mechanical strength of the insulator.

(b) Wherever grounded metal pins or grounded crossarms or metal towers are used at a cross-over span support of grade A or B construction, with wood pins or crossarms or poles used within five spans of the crossing, the insulators used on such grounded or metal supports shall be capable of withstanding a voltage 50 per cent. higher than those in other portions of the line. Where strain insulators are used, they shall be capable of withstanding under their normal mechanical stress, at least as high a voltage as the line insulators in general, or shall be capable, when not under mechanical stress, of withstanding a voltage 25 per cent. greater.

(c) Insulators in grades A and B construction should be so designed that their dry flash-over voltage is not more than 75 per cent. of their puncture voltage at a frequency of 60 cycles.

(d) Insulators to which are attached conductors in grades A or B construction shall be capable of withstanding without flash over at the frequency of 60 cycles the voltages shown in the following table:

TABLE 5 OF CODE.—TEST VOLTAGES FOR WET AND DRY FLASH-OVER

VOLTAGE OF CIRCUIT	FLASH-OVER VOLTAGE	
	Dry	Wet
750	5,000	3,500
2,300	11,000	8,000
4,000	17,000	13,000
6,600	27,000	20,000
7,500	30,000	22,000
11,000	40,000	30,000
22,000	75,000	55,000
33,000	105,000	75,000
44,000	135,000	95,000
55,000	160,000	115,000
66,000	185,000	135,000
88,000	235,000	170,000
110,000	285,000	200,000
150,000	375,000	225,000
200,000	490,000	250,000

By the term "wet" is meant a condition equivalent to a precipitation of one-fifth inch of rain per minute at an angle of 45 degrees to the axis of the insulator.

(e) Each completed pin-type insulator for line voltages over 15,000 where used in construction of grades A or B, and each completed suspension insulator disk, shall be subjected to a routine factory test at dry flash-over voltage at a frequency of 60 cycles or any other test which may be generally sanctioned by good modern practice.

(f) In installing the insulators and conductors of grades A and B construction precautions shall be taken to guard against the possibility of arcs or leakage current injuring conductors or burning any wooden parts of the supporting structure which would render the conductors liable to fall.

264. CROSSOVER WIRE CLEARANCES TO RAILWAY WIRES. The clear space between the lowest overhead supply line conductor or guy or span wire crossing over any conductor or wire concerned in the operation of the railway (except for crossings between conductors and guy or span wires on the same poles) shall not be less than given below, 60° F., with no wind or other mechanical loading of the conductors or wires, where the upper conductor or wire has fixed supports (pin or strain-type insulators), and the sum of the distances from the point of intersection to the nearest supporting structure of each span, does not exceed 100 feet.

(a) Above signal conductors (of railways):

	FEET
Supply lines 0 to 750 volts	4
This may be reduced to 2 feet if the crossing is not within 6 feet of any pole concerned in the crossing and the voltage is not over 300 volts.	
Supply lines, 750 to 7500 volts	4
Supply lines, 7500 to 50,000 volts	6
Service supply connections	2
Guy, messenger, and span wires	2

(b) Above supply conductors (over 400 volts to ground and supplying railway signal systems):

	FEET
Supply lines, 0 to 750 volts	2
Supply lines, 750 to 7500 volts	2
Supply lines, 7500 to 50,000 volts	4
Guy, messenger, and span wires	4

(c) For clearances above trolley contact conductors, see section 27.

(d) Above guys, messenger, and span wires (of railways):

	Feet
Supply conductors, 0 to 750 volts	2
Supply conductors, 750 to 50,000 volts	4
Guy, messenger, and span wires of supply lines	2

Guys, span wires, and messenger wires may be either above or below the conductors by the given clearances.

265. INCREASE OF CLEARANCES IN SPECIAL CASES. (a) *Clearance Increase for Long Spans.*—The clearances of rule 264 shall be increased where the sum of the distances from the point of intersection to the nearest supporting structure of each span exceeds 100 feet by 2 inches for each 10 feet of the excess between 100 and 200 feet, and by 2 inches for each 20 feet of the excess beyond 200 feet.

(b) *Clearance Increase for High Voltage.*—The clearances of rule 264 shall be increased, where the supply line voltage exceeds 50,000 volts, by 0.5 inch per 1000 volts excess.

(c) *Clearance Increase for Suspension Insulators.*—The initial clearances, where the upper line at a grade A or B crossing over track rails or signal lines is supported by suspension insulators, shall be sufficient to prevent the minimum clearances of rule 263 and 264 from being reduced through the breaking of a conductor in either adjoining span by more than 10 per cent. over rails or by more than 25 per cent. over conductors or wires.

Mechanical Data for Copper Wire—From Appendix A of Code

The following table contains data on the ultimate strength and per cent. of elongation before failure of hard, medium, and soft copper wire as given in the 1915 report of the A. S. T. M.

The elastic limit as given by the same society is 55 to 60 per cent. of the ultimate strength for hard-drawn copper and 50 to 55 per cent. for medium-drawn copper. There is no definite elastic limit for soft copper, but its behavior, after having a slight preliminary stretch, may be considered as approximately that of an elastic material having a limit of elasticity of 10,000 to 15,000 pounds per square inch.

The modulus of elasticity has been taken at 16,000,000 for all grades of copper.

TABLE 21 OF CODE.—MECHANICAL DATA FOR COPPER WIRE (FROM CODE APPENDIX A)

Size A. W. G.	Diameter	Hard Drawn		Medium Drawn			Soft Drawn	
		Average Ultimate Tension	Average Elongation	Average Minimum Ultimate	Average Maximum Ultimate	Elongation	Average Ultimate Tension	Average Elongation
	Inches	Pounds	Per cent.	Pounds	Pounds	Per cent.	Pounds	Per cent.
No. 8	0.128	63,700	1.06	49,660	56,660	1.08	..	..
No. 6	.162	62,100	1.14	49,000	56,000	1.15	..	..
No. 4	.204	60,100	1.24	48,330	55,330	1.25	37,000	30
No. 2	.258	57,600	1.98	47,000	54,000	2.50	..	..
No. 1	.289	56,100	2.17	46,000	53,000	2.75	..	..
No. 0	.325	54,500	2.40	45,000	52,000	3.00	..	..
No. 00	.365	52,800	2.80	44,000	51,000	3.25	36,000	35
No. 000	.41	51,000	3.25	43,000	50,000	3.60	..	..
No. 0000	.46	49,000	3.75	42,000	49,000	3.75	..	..

Resultant Conductor Loadings

Table 22 gives the resultant loading in pounds per 100 feet for conductors of various sizes and materials in regions of heavy, medium, and light loading. The calculations are based on the assumed loadings given in rule 222 and on average values of the diameters of weather-proof wires. The over-all diameters of covered wires supplied by different manufacturers vary considerably and hence average values are chosen.

Table 22 of Code.—Resultant Loadings in Pounds per 100 Feet for Conductors (From Code Appendix A)

Size A. W. G.	Diameter in Inches Over All	Weight of Conductor in Pounds Per 100 Feet	Resultant Loading in Pounds Per 100 Feet		
			Heavy Loading	Medium Loading = ⅔ Heavy	Light Loading = 4/9 Heavy
Bare solid copper:					
No. 8	0.128	5.0	77.2	51.5	34.4
No. 6	.162	7.9	91.7	61.1	40.7
No. 4	.204	12.6	98.1	65.5	43.5
No. 2	.258	20.1	107.5	71.7	47.7
No. 1	.289	25.3	113.7	75.7	50.5
No. 00	.365	40.3	130.9	87.3	58.2
No. 0000	.460	64.1	157.5	105.0	[a]80.1
T.B.W.P. solid copper:					
No. 8	.26	7.5	100.3	67.0	44.7
No. 6	.32	11.2	107.5	71.7	47.8
No. 4	.38	16.4	116.4	77.7	51.8
No. 2	.44	26.0	127.8	85.8	56.7
No. 1	.47	31.6	134.5	89.7	59.7
No. 00	.53	50.2	153.2	102.2	68.2
No. 0000	.65	76.7	185.0	123.5	[a]96.0
T.B.W.P. stranded copper:					
No. 2	.444	27.0	128.5	85.5	57.2
No. 1	.518	32.8	139.5	92.8	62.0
No. 00	.662	52.2	166.6	111.0	74.0
No. 0000	.785	80.0	199.3	133.0	[a]100.0
250,000 cir. mils	.862	98.5	221.7	147.5	[a]123.0
350,000 cir. mils	.978	134.5	261.9	174.2	[a]168.0
500,000 cir. mils	1.108	189.4	321.7	[a]237.0	[a]237.0
750,000 cir. mils	1.343	282.2	427.2	[a]353.0	[a]353.0
1,000,000 cir. mils	1.531	367.4	523.0	459.0	[a]459.0
Bare stranded aluminum:					
No. 2	.291	6.1	102.3	68.2	45.5
No. 1	.328	7.7	106.5	71.0	47.4
No. 00	.414	12.2	116.8	78.0	51.8
No. 0000	.522	19.5	131.2	87.5	58.4

[a] These values are 25 per cent. greater than the weight of the conductor. (See rule 222 a-2 and 222 a-3.)

Loading Data, Mechanical Characteristics, and Recommended Transverse Strength of Overhead Line Supports—From Code Appendix B

1. Data for Computing Transverse and Vertical Strength Required for Line Supports. (a) *Assumed Transverse Pressures and Vertical Loads on Conductors of Various Materials and Sizes.*—The values of transverse loads computed from rule 230 for various combinations of hazard (A. B, or C) and of loading districts (H, M, or L) are given in Table 23 (of Code.)

Table 23 of Code.—Transverse Wind Pressures in Pounds per Conductor per 100 Feet (From Code Appendix B)

Size A. W. G.	Diameter in Inches Over All	Heavy Loading			Medium Loading M=⅔ H			Light Loading L=½ M=⅓ H		
		A H	B H	C H	A M	B M	C M	A L	B L	C L
Bare solid copper:										
No. 8	0.128	113	66	38	75	44	25.0	50.0	29.3	16.7
No. 6	.162	116	68	39	77	45	25.7	51.6	30.4	17.2
No. 4	.204	120	70	40	80	87	26.7	53.4	31.1	17.8
No. 2	.258	126	73	42	84	49	28.0	56.0	32.5	18.7
No. 1	.289	129	75	43	86	50	28.7	57.4	33.3	19.1
No. 00	.365	136	79	45	91	53	30.7	60.5	35.1	20.2
No. 0000	.460	146	85	49	97	57	32.3	65.0	37.8	21.7
T.B.W.P. solid copper:										
No. 8	.26	126	73	42	84	49	28.0	56.0	32.5	18.7
No. 6	.32	132	77	44	88	51	29.3	58.7	34.2	19.6
No. 4	.38	138	80	46	92	54	30.7	61.4	35.8	20.5
No. 2	.44	144	84	48	96	56	32.0	64.0	37.3	21.3
No. 1	.47	147	86	49	98	57	32.7	65.4	38.2	21.8
No. 00	.53	153	89	51	102	59	34.0	68.0	39.6	22.7
No. 0000	.65	165	96	55	110	64	36.7	73.4	42.7	24.5
T.B.W.P. stranded copper:										
No. 2	.444	144	84	48	96	56	32.0	64.0	37.3	21.3
No. 1	.518	152	88	51	101	59	33.7	67.4	39.3	22.5
No. 00	.662	166	97	55	111	65	36.9	73.8	43.2	24.6
No. 0000	.785	178	104	59	119	69	39.7	79.4	46.3	26.5
250,000 cir. mils	.862	186	108	62	124	72	41.4	82.8	48.2	27.6
350,000 cir. mils	.978	198	115	66	132	77	44.0	88.0	51.2	29.3
500,000 cir. mils	1.108	211	123	70	140	82	46.8	93.6	54.8	31.2
750,000 cir. mils	1.343	234	136	78	156	91	52.1	104.2	60.8	34.4
1,000,000 cir. mils	1.531	253	147	84	169	98	56.2	112.4	65.6	37.5
Bare stranded aluminum:										
No. 2	.291	129	75	43	86	50.2	28.7	57.4	33.5	19.1
No. 1	.328	133	78	44	89	51.7	29.3	59.1	34.5	19.5
No. 00	.414	141	82	47	94	54.8	31.3	63.0	36.6	20.9
No. 0000	.522	152	89	51	101	59.1	34.0	68.0	39.3	22.7

The vertical loads on conductors based on the assumptions of rule 232 a (1) are given in Table 24 of Code. Values for transverse and vertical loadings for wires of other sizes and materials can be readily computed.

Table 24 of Code.—Vertical Loads on Conductors (From Code Appendix B)

Size A. W. G.	Vertical Weight in Pounds Per 100 Feet		
	Heavy = Conductor + 0.5 Inch Ice	Medium = Conductor + 0.25 Inch Ice	Light = Conductor Only
Bare solid copper:			
No. 8	44.0	16.7	6.0
No. 6	49.1	20.7	7.9
No. 4	56.4	26.7	12.6
No. 2	67.3	36.0	20.1
No. 1	74.4	42.0	25.3
No. 00	94.0	59.4	40.3
No. 0000	123.8	86.1	64.1
T.B.W.P. solid copper:			
No. 8	54.7	23.4	7.5
No. 6	62.7	29.1	11.2
No. 4	69.8	35.3	16.4
No. 2	84.3	47.4	26.0
No. 1	90.9	53.5	31.6
No. 00	113.3	74.5	50.2
No. 0000	147.6	104.7	76.7
T.B.W.P. stranded copper:			
No. 2	85.5	48.6	27.0
No. 1	96.1	56.7	32.8
No. 00	124.5	80.6	52.2
No. 0000	159.9	112.2	80.0
250,000 cir. mils	183.2	133.1	98.5
350,000 cir. mils	226.4	172.8	134.5
500,000 cir. mils	289.4	231.6	189.4
750,000 cir. mils	397.7	331.8	282.2
1,000,000 cir. mils	495.0	423.1	367.4
Bare stranded aluminum:			
No. 2	53.3	22.9	6.1
No. 1	59.2	25.4	7.7
No. 00	69.1	32.8	12.2
No. 0000	83.1	43.6	19.5

TABLE 79.—DETAILS OF TRANSMISSION SYSTEMS OF THE WORLD OPERATING AT AND ABOVE 70,000 VOLTS

Compiled for the ELECTRICAL WORLD by Selby Haar

No.	Transmission Lines																			Ltg. Prot.		Switch Plant, Mfr.
	Termini	Dist. of Trans., Mi.	Steel Towers or Wood Poles	Height, Ft.	Span		Circuits		Conductors						Insulators				Overhead Ground Wires per Tower		Type, Al. Cell, Horn, Res., Etc.	Manufacturer	
															Ordinary		Strain						
					Normal Ft.	Max. Ft.	Per Tower	Total	Section-Gage and Sq. In.	Material	Strands	Core	Arrangement	Spacing, In.	Sections and Type	Manufacturer	Sections and Type	Manufacturer	Mat.-Size	Number			
1	Big Creek–Los Angeles, Cal.	241	S.T.	Ca. 48–	660	2900	1	2	605,000 Circ.M. 0.475. 78,000 Circ.M. 0.061	Al.	54 7	St.	H.	210	9–Susp.	Locke	11–Susp.	Locke	St. ½ In.	1	Al.	W. G.E.	W. G.E.
2	Au SableBattle–Creek, Mich.	245	S.T.	40–167	500	600?	1	1	O. B. & S. 0.083	Cu.	7	Cu.	.:	208 Slant 144 Vert.	10–Susp	Oh. Br.	10–Susp.	Oh. Br.	No.	No	Al.	G.E.	G.E.
3	Bishop–San Bernardino, Cal.	239	S.T.	70–	660	1500	2	2	211,160 Circ.M. 0.166. 34,970 Circ. M.0.027	Al.	6 1	St.	.:	134 Min.	6–Susp.	Locke Oh. Br.	6–Susp.	Locke Oh. Br.	St. ⅜ In.	1	Al.	G.E.	W. Bowie
4	Grace, Idaho–Salt Lake City, Utah	135	S.T.	82–	650	2200	2	2	250,000 Circ.M. 0.196	Cu.	12	Cu.	V.	156 Min.	9–Susp.	Thomas Oh. Br.	11–Susp.	Thomas Oh. Br.	St. ⅜ In.	2	Al.	G.E.	G.E.
5	Drum–Cordelia, Cal.	110	S.T.	82– 50–	800	2350	1 and 2	1	00000 B. & S. 0.210	Cu. Al.	7 19	Cu. Al.	H. and V.	162 120	7–Susp.	Oh. Br.	8–Susp.	Oh. Br.	No	No	No	. .	P.G. & El.
6	Cheat Haven–Butler, Pa.	106	S.T.	44– 80	528	. .	2	2	O. B. & S. 0.083	Cu.	6	Cu.	V.	60	5–Susp.	Penna. China Co.	5–Susp.	Penna. Co.	Cu.-Clad 4	2	Al.	W.	W.
7	Cleveland–Nashville, Tenn.	140	S.T.	50–210	663	1903	1 and 2	2	00 B. & S. 0.105	Cu.	7	Cu.	H.	126	7–Susp.	Oh. Br.	8–Susp.	Oh. Br.	St. 5-16 In.	1	Al.	G.E.	W. G.E.
8	Shelburne Falls–Millbury, Mass.	60	S.T.	75–	600	1200	2	2	00 B. & S. 0.105	Cu.	7	Cu.	V.	120	6–Susp.	Locke	7–Susp.	Locke	St. ⅜ In.	1	Al.	G.E.	G.E.
9	Lake Inawashiro Tokio, Japan–	144	S.T.	70–220	550	1530	2	4	100 Sq. Mm. 0.155	Cu.	7	Cu.	.:	122 Slant 120 Vert.	7–Susp.	Special Thomas	8–Susp.	Special Thomas	St. ⅜ In.	2	Al.	W.	W.
10	Croton–Grand Rapids and Muskegon, Mich.	35	S.T.	53– 60	528	. .	1	2	2 B. & S. 0.052	Cu.	6	Hemp	.:	96	5–Susp.	G.E.	5–Susp.	G.E.	No	No	Al.	G.E.	W.

11	Niagara Falls–Toronto and St. Thomas, Can.	135 90	S.T.	61.3–170	550	1100	2	2	0000 B. & S. 0.166. 000 B. & S. 0.132	Cu. Al.	7	St. Cu. Al.	.·. and V.	128 96	8-Susp.	Locke Oh. Br. Hermsdorf	10-Susp.	Locke Oh. Br. Hermsdorf	St.	2 and 3	Al.	W. G.E.	W. G.E.
12	Lauchhammer Mines–Riesa, Germany	35	S.P.	60– 65	550	900	2	2	42 Sq. Mm. 0.066	Cu.	7	Cu.	.:	70	5-Susp.	Hermsdorf	6 7-Susp.	Rosenthal	St. 100000 Circ.M.	1	Horn and Res.	S.-S.	S.-S.
13	Tallulah Falls–Lindale, Atlanta, Ga., etc.	210	S.T.	66–105	550	1200	2	2	0000 B. & S. 0.166. 00 B. & S. 0.105	Cu.	7	Cu.	V.	108	4 5-Susp.	Thomas Oh. Br.	5-Susp.	Thomas	St. 7-16 In.	2	Al.	G.E.	W. G.E.
14	Coosa River–Birmingham, etc., Ala.	150	S.T.	65– 68	600– 700	900–1200	2	2	00 B. & S. 0.105	Cu.	7	Cu.	.:	122 Slant 120 Vert.	6-Susp.	Locke Thomas Oh. Br.	7-Susp.	Locke Thomas Oh. Br.	St.	2	Al.	W. G.E.	W. G.E.
15	Keokuk, Ia.–St. Louis, Mo.	144	S.T.	79–231	800	3300	2	2	300,000 Circ.M. 0.235	Cu.	19	Cu.	V.	120	7-Susp.	Locke Oh. Br.	8-Susp.	Locke Oh. Br.	St. ½ In.	1	Al.	G.E.	G.E.
16	Hauto–Siegfried, Pa.	24	S.T.	78.5	600	2000	2	2	250,000 Circ.M. 0.196	Cu.	7	Cu.	V.	120	6-Susp.	Locke	Susp.	Locke	St. ⅜ In.	2	Al.	W.	W.
17	Cedar Rapids, Can.–Massena, N. Y.	60	S.T.	70	660	..	2	2	500,000 Circ.M.	Al.	..	St.	V.	120	..	..	..	..	..	1	Al.	..	..
18	Boquila–Parral, Chihuahua, Mexico	157	S.T.	65– 90	575	1100	2	2	Equi. Cu. 0000 B. & S. 0.166	Al.	7	Al.	.:	122 Slant 120 Vert.	5 7-Susp.	Locke Oh. Br.	9-Susp.	Oh. Br.	St. ⅜ In.	3	Al.	G.E.	G.E.
19	Segre River–Barcelona, Spain	105	S.T.	65–	750	1500	2	4	0000 B. & S. 0.166	Cu.	7	Cu.	△	96	Misc.Pin	Several	7-Susp.	Several	St. ⅜ In.	1	Al.	G.E.	G.E.
20	Tocopilla–Chuquicamata, Chile	86	S.T.	47–	656	..	1	1	000 B. & S. 0.132	Cu.	7	Cu.	H.	155	Susp.	Locke	Susp.	Locke	St. ⅜ In.	2	Horn and Res.	S.-S.	S.-S.
21	Mill Creek–Oakland, Cal.	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
22	Stanislaus–San Francisco, Cal.	138	S.T.	65–	850	1600	2 and 1	2	00 B. & S. 0.105	Cu.	6	Hemp	V.	96	5-Susp.	Oh. Br. Locke	5-Susp.	Oh. Br. Locke	No	No	Al.	G.E.	G.E.
23	Great Falls–Butte and Anaconda, Mont.	150	S.T.	45–	600	3034	1	2	0 B. & S. 0.083	Cu.	6	Hemp	H.	124	6-Susp.	Oh. Br.	12-Susp.	Oh. Br.	St.	2	Al.	G.E.	W. G.E.

TABLE 79.—DETAILS OF TRANSMISSION SYSTEMS OF THE WORLD OPERATING AT AND ABOVE 70,000 VOLTS—(*Continued*)

No.	Termini	Transmission Lines																			Ltg. Prot.		Switch Plant Mfr.
		Dist. of Trans., Mi.	Steel Towers or Wood Poles	Heigth, Ft.	Span		Circuits		Conductors						Insulators				Overhead Ground Wires per Tower		Type, Al. Cell, Horn, Res., Etc.	Manufacturer	
					Normal Ft.	Max. Ft.	Per Tower	Total	Section-Gage and Sq. In.	Material	Strands	Core	Arrangement	Spacing, In.	Ordinary		Strain		Mat.-Sise	Number			
															Sections and Type	Manufacturer	Sections and Type	Manufacturer					
24	Blewitts Falls–Raleigh and Lumberton, N.C	96	S.T.	72.6–	650	1455	2	2	0 B. & S. 0.083	Cu.	6	None	V.	108	7-Susp. 6-Susp.	Thomas	7-Susp.	Thomas	St. ⅜ In.	1	Al.	G.E.	G.E.
25	Glenwood–Denver, Colo.	152	S.T.	44.2–	660	2900	1	1	0 B. & S. 0.083	Cu.	6	Hemp	H.	132	4-Susp. 5-later	G.E.	4 5-Susp.	G.E.	No	No	No	No	G.E.
26	Big Bend–Oakland, Cal.	154	S.T.	75–210	750	2740	2	2	000 B. & S. 0.132	Cu.	7	..	V.	120	5-Susp.	Oh. Br. Thomas	Susp.	Oh. Br. Locke Thomas	St. ⅜ In.	1	Al.	G.E.	G.E.
27	Great Falls, S. C. Durham, N. C.	210	S.T.	75–	600	1800	1 and 2	2	00 B. & S. 0.105	Cu. Al.	7	Cu. Al.	V.	124	4-Susp. 6-Susp. 4-Susp.	Thomas Oh. Br. Locke	5-Susp. 8-Susp. 5-Susp.	Thomas Oh. Br. Locke	St. ⅜ In.	1	Al.	W. G.E.	G.E. W.
28	Shawinigan Falls–Montreal, Can.	87	S.T	70.6–	520	1400	2	2	250,000 Circ.M. 0.196	Al.	19	Al.	V.	96	7-Susp.	Oh. Br.	8-Susp.	Oh. Br.	St. ⅜ In.	2	Al.	G.E.	W.
29	San Francisquito–Los Angeles, Cal.	47	S.T.	50–	650	1750	2	4	250,000 Circ.M. 0.196. 300,000 Circ. M.0.235	Cu.	19	Cu.	V.	120	7-Susp.	Oh. Br.	8-Susp.	Oh. Br.	St.	1	Al.	..	W.
30	Khopoli–Bombay, India	43	S.T.	66–160	500	1175	2	2	0.095	Cu.	..	..	∴	126	6-Susp.	Bullers	7-Susp.	Bullers	Yes	..	Al.	G.E.	G.E.
31	Germany	155 65	..	..	645	..	..	..	..	Cu.	..	..	..	..	5-Susp.	Hermsdorf	6-Susp.	Hermsdorf	..	..	..	..	..
32	Pescara River–Naples, Italy	124	S.P.	59.4–65	656	1174	1	2	66 Sq. Mm. 0.102	Cu.	7	Cu.	..	85	1-Pin	Richard Ginori	1-Pin	Richard Ginori	No	No	Horn & Water Jet	Br. Bov.	Br. Bov.
33	New River–Roanoke, Va., Coalwood and Bluefield, W.V	75	W.P.	39–	250	1200	1	1	0 B. & S. 0.083	Al.	7	Al.	∴	96	4-Susp.	Thomas	5-Susp.	Thomas	St. ⅜ In.	1	Al.	G.E.	G.E.
34	Lages River–Rio Janeiro, Brazil	51	S.T.	56– 71	400 500	1935	2	4	000 B. & S. 0.132	Cu.	6	Hemp	△	96	Misc. Pin	Thomas	5-Susp.	Locke	St. ⅜ In.	1	Horn and Liq.	W. G.E.	W.

35	Sorocaba–Sao Paulo, Brazil	56	S.T.	65	750	1200	2	4	00 B. & S. 0.105	Cu.	7	Cu.	△	96	Misc.Pin	Several	5-Susp.	Several	St. ⅜ In.	1	Al.	G.E.	G.E.
36	River Ouse–Hobart, Tasmania	64	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Al.	W.	W.
37	Necaxa–Mexico City, Mexico	169	S.T.	52–	500 750	1500	2	4	0000 B. & S. 0.166	Cu.	6	Hemp	∴	72	3-Pin	Thomas	3-Pin	Thomas	St.	1	Al.	G.E.	G.E.
38	Niagara Falls–Toronto, Can.	80	S.T.	52– 65–	400 650	800	2	4	190,000 Circ.M. 0.149	Cu.	7	Cu.	△	72 96	Misc.Pin	Locke Thomas	5-Susp.	Locke	St. ⅜ In.	1	Horn	G.E.	S.-S. G.E.
39	Vereenigung–Johannesburg, South Africa	30	S.T.	53– 71	500	..	2	4	60 Sq. Mm. 0.093	Cu.	Yes	..	.:	110	6-Susp.	G.E.	6-Susp.	G.E.	St. 35 Sq.Mm.	3	Horn & Res. Al.	A.E.G G.E.	S.-S. A.E.G W.
40	Hannawa Falls–Potsdam, N. Y.	60	S.T.	..	550	..	..	..	O. B. & S. 0.083	Al.	..	..	..	108	5-Susp.	Locke	6-Susp.	Locke	Yes	2	..	..	..
41	Spain	..	..	..	..	..	..	2	..	..	..	..	..	..	Susp.	..	Susp.	..	..	..	..	..	..
42	Porjus–Kiruna, Sweden	73.4	S.P.	..	Ca.640	..	4	4	50–80 Sq. Mm. 0.077–0.124	..	..	..	..	..	Susp.	..	Susp.	..	..	..	..	..	..
43	Komahashi-Tokio, Japan	48	S.T.	..	450	850	1 and 2	2	18–No 12 B.W. G.0.168	Cu.	18	Hemp	Triangular	84	4-Pin	Nippon Toki G.K.	..	..	St. 3 B.&S.	1	Al.	G.E.	G.E.
44	Kern River–Los Angeles, Cal.	117	S.T.	30– 60	700	1500	2	2	0000 B. & S. 0.166	Cu.	7	Cu.	∴	72	4-Pin and Susp.	Oh. Br. Thomas Locke	Pin	Oh. Br.	No.	No	Multiplex Al.	G.E.	G.E.
45	Rogers Dam–Muskegon, Mich	66	W.P.	35– 75	132	..	1	1	2 B. & S. 0.052	Cu.	No	Cu.	△	80 Av.	3-Pin	Locke	3-Pin	Locke	St. No. 10	1	Stat. Int. & M.G.	W.	W.
46	Grossoto–Milan, Italy	93	S.P.?	65.6	656	1066	2	4	80 Sq. Mm. 0.124 Sq. In.	Cu.	19	Cu.	..·	63	Pin	Richard Ginori	Pin	Richard Ginori	No	No	H&R., W.J., Cyl.	Several	Br. Bov.
47	Cedegolo–Milan, Italy	72	S.P.	60–	607	..	1	2	79 Sq. Mm. 0.122	Cu.	..	..	.:	75	4-Pin	Osculati and Carini	4-Pin	Osculati and Carini	No	No	Horn and Res.	A.E.G	A.E.G
48	Canyon Ferry, Hauser Lake–Butte, Mont.	100	W.	40–	110	200	1	2	0 B. & S. 0.083	Cu.	7	Cu.	∴	72	1 Pc. Glass	Hemingray	Glass	Hem.	No	No	Al.	W.	W.
49	Molinar–Madrid, Spain	158	W.P.	40– 50	328	..	2	2	50 Sq. Mm. 0.155	Cu.	1	Cu.	∴	71	Pin	Hermsdorf Rosenthal	Pin	Hermsdorf Rosenthal	No	No	Horn and Res.	S.-S.	S.-S.

TABLE 79.—DETAILS OF TRANSMISSION SYSTEMS OF THE WORLD OPERATING AT AND ABOVE 70,000 VOLTS—(*Continued*)

No.	TRANSMISSION LINES																				LTG. PROT.		SWITCH PLANT MFR.
	Termini	Dist. of Trans., Mi.	Steel Towers or Wood Poles	Height, Ft.	Span		Circuits		Conductors						Insulators				Overhead Ground Wires per Tower		Type, Al. Cell, Horn, Res., Etc.	Manufacturer	
															Ordinary		Strain						
					Normal Ft.	Max. Ft.	Per Tower	Total	Section-Gage and Sq. In.	Material	Strands	Core	Arrangement	Spacing, In.	Sections and Type	Manufacturer	Sections and Type	Manufacturer	Mat.-Size	Number			
50	Holtwood, Pa.–Baltimore, Md.	40	S.T.	40–	500	1750	2	4	300,000 Circ.M. 0.235	Al.	..	Al.	V.	84	5-Susp. 7-Susp.	Oh. Br.	6-Susp. 8-Susp.	Oh. Br.	St. ⅜ In.	1	Al.	G.E. W.	G.E.
51	Campania Hidro-Elec. e Irrigadora del Chapala S.A.	180	S.T.	59	645	1000	2	2	99,000 Cm. 0.098 50 Sq. Mm.	Cu.	.	Cu.	∴	185	3-Susp.	Hermsdorf	6-Susp.	Hermsdorf	..	1	Horn & Resist	S.-S.	S.-S.
52	S. Damazzo–Novi, et al., Italy	155	S.P.	39.4	494	2300	2	4	78 Sq. Mm. 0.121 Sq. In.	Cu.	.	Cu.	△	65	Pin	Richard Ginori	Pin	Richard Ginori	No?	..	Horns, W.J., Con.	A.E.G Friburg	A.E.G Br. Bov.
53	Porjus–Kiruna, Sweden	73.4	S.T.	..	625	740	2	2	40 Sq. Mm. 0.062	Cu.	..	..	H.	158	6-Susp.	..	6-Susp.	..	35 Sq.Mm. Iron	1	Horn and Res.	..	..
54	Point Dubois–Winnipeg, Can.	77	S.T.	42– 90	600	939	2	2	278,600 Circ.M. 0.219	Al.	19	Al.	△	72	4-Pin	Locke	4-Pin	Locke	Yes in exp. places	1	Al.	W.	W.

Note: The above tables present data only for systems operating at 70,000 volts or above. The present station equipment rating represents that which the transmission lines call for under normal conditions. In all cases the figures are based on generator ratings as given by manufacturers. The transmission distance is that between the points mentioned and represents the farthest point to which energy is transmitted at the voltage given. The total mileage of the system is not given. The following abbreviations are used:

Al.—aluminum
Conn.—connection
Cu.—copper
Cyl.—cylinder
H.—hydraulic or horizontal
H. and R.—horn and resistance
H. T.—high tension
Liq.—liquid
L. T.—low tension
M. G.—multiple gap
Mat.—material
Min.—minimum
Prot.—protection
Res.—resistance
S.—steam
St.—steel
Stat.—static interrupters
Susp.—suspension
Str.—strands
S. P.—steel poles
S. T.—steel towers
V.—vertical
W. J.—water jet
W. P.—wood pole*

* The data in these tables are condensed from an article by Selby Haar, which was published in the *Electrical World*, April 25, 1914.

TABLE 79.—DETAILS OF TRANSMISSION SYSTEMS OF THE WORLD OPERATING AT AND ABOVE 70,000 VOLTS—(*Continued*)

Compiled for the ELECTRICAL WORLD by Selby Haar

No.	Name	Operating Voltage	Frequency Cycles	Rating of Plant, Kw		Beginning of Operation	Turbines						Generators					Step-up Transformers							Step-down Transformers			
				Present	Ultimate		Hydr. or Steam	H.P.	Head Ft.	R.P.M.	Shaft Hor. or Vert.	Manufacturer	Kva.	Kw.	P.F.	Voltage	Manufacturer	Kva.	Phases	Conn. L. T.	Conn. H. T.	Y Gr. Dir. or with Res.	Total Kva. Connected to Transmission Lines	Manufacturer	Line Voltage L.T.	Line Voltage H.T.	Conn. L. T.	Conn. H. T.
1	Pacific Light & Power Co.	150,000	50	59,500	300,000	1913	H.	2x10,000	1780 1900	375	H.	Al. Ch.	17,500	14,875	.85	6,600	W. G.E.	5,833	1	Δ	Y	D.	70,000	W. G.E.	72,000 18,000	150,000	Δ	Δ
2	Au Sable Elec. Co.	140,000	60	19,000	86,500	1912	H.	3,500 4,150	26 35 40	120 164 180	H.	Al. Ch.	2,200 3,333 3,333	2,000 3,000 3,000	.90	2,500	G.E.	3,000	1	Δ	Δ	No	19,000	G.E.	5,000 22,000 44,000	140,000	Δ	Δ
3	Southern Sierras Power Co.	140,000	60	8,750	40,000	1915	H.	3,300	814 and 258	300 164	H.	Henry Pelton Doble	2,250 2,000	2,250 2,000	1.	2,200	C.W. Al. Ch.	750 2,000	1	Δ	Y	R.	8,250	W.	33,000 to 4,000	138,500 140,000	Δ	Y
4	Utah Power & Light Co.	100,000	60	33,000	84,000	1914	H.	16,500 15,000	482 140	514 180	V.	I.P. Morris	12,222 11,111	11,000 10,000	.90	6,600	W. G.E.	4,000	1	Δ	Δ	No	24.000	G.E.	44,000	120,000	Δ	Δ
5	Pacific Gas & Electric Co.	125,000 to 110,000	60	25,000	142,500	1913	H.	2x8500	1375	360	H.	Pelton Doble	12,500	10,000	.80	6,600	W.	4,250	1	Δ	Y	D.	25,500	Al. Ch.	60,000	100,000	Y	Y
6	West Penn. Trac. & Water Po'r Co.	125,000	60	32,000	105,000	1914	H.	12,000	82	144	V.	W.S.M.	10,000	8,000	.80	6,600	Al. Ch.	10,000	3	Δ	Δ	No	40,000	Al. Ch.	22,000 6,600	120,000	Δ	Δ
7	Tennessee Po'r Co.	120,000	60	15,000	75,000	1914	H.	10,000	250	360	H.	I.P. Morris	9,375	7,500	.80	6,600	W. G.E.	9,375	3	Δ	Δ	No	18,750	W. G.E.	13,200	120,000 to 95,000	Δ	Δ
8	Conn. River Trans. Co.	120,000	60	14,400	14,400	Ca 1914	H.	Ca. 3,300	57 to 64	257	H.	W.S.M.	2,000	1,600	.80	2,300	G.E.	3,000	3	Δ	Y	D.	18,000	G.E.	13,200	110,000	Δ	Δ & Y
9	Inawasniro Hydro-elec. Po'r Co.	115,000	50	42,000	73,500	1914	H.	Ca. 10,000	350	375	H.	Voith	7,700	7,000	.91	6,600	Dick Kerr	4,400	1	Δ	Δ	No	52,800	W.	11,000	100,000	Δ	Δ
10	Au Sable Electric Co.	110,000	30	9,000	15,000	1906	H.	14,400	40	225	H.	Loffel	3,000	3,000	1.	6,600	W.	3,750	1	Δ	Δ	No	11,250	W.	19,000 7,200	. .	Δ	Δ

TABLE 79.—DETAILS OF TRANSMISSION SYSTEMS OF THE WORLD OPERATING AT AND ABOVE 70,000 VOLTS—(*Continued*)

No.	NAME	OPERATING VOLTAGE	FREQUENCY CYCLES	RATING OF PLANT, KW		BEGINNING OF OPERATION	TURBINES						GENERATORS					STEP-UP TRANSFORMERS							STEP-DOWN TRANSFORMERS			
				Present	Ultimate		Hydr. or Steam	H.P.	Head Ft.	R.P.M.	Shaft Hor. or Vert.	Manufacturer	Kva.	Kw.	P.F.	Voltage	Manufacturer	Kva.	Phases	Conn. L.T.	Conn. H.T.	Y. Gr. Dir. or with Res.	Total Kva. Connected to Transmission Lines	Manufacturer	Line Voltage L.T.	Line Voltage H.T.	Conn. L.T.	Conn. H.T.
11	Hydro-Elec. Po'r Com. of Ontario	110,000	25	106,800	175,000	1910	H.	12,500 12,500 13,400	175	187½	H.	Voith W.S.M.	7,500 8,950 9,700	7,500 8,950 9,700	1.	12,000	W. G.E.	3,500	1	Δ	Y	R.	42,000	W.	26,400 13,200 6,600	110,000	Δ	Y
12	Lauchhammer, A. G.	110,000	50	15,000	20,000	1911	S.	..	..	1000	H.	A.E.G. M.A.N.	14,300 6,250	10,000 5,000	.70 .80	5,000 5,000	A.E.G. S.-S.	6,250	3	Y	Y	No	20,000	S.-S.	60,000 15,000	110,000	Y	Y
13	Georgia Ry. & Power Co.	110,000	60	50,000	63,000	1912	H.	17,000	580	514	V.	S.M. Smith	12,500	10,000	.80	6,600	G.E.	3,333	1	Δ	Y	R.	60,000	G.E.	22,000 11,000	110,000	Δ	Δ
14	Alabama Po'r Co.	110,000	60	48,000	300,000	1913	S.	17,500	68	100	V.	I.P. Morris	14,000	12,000	.85	6,600	W.	4,667	1	Δ	Y	R.	56,000	W.	22,000	110,000	Δ	Δ & Y
15	Mississippi River Power Co.	110,000	25	112,500	225,000	1913	H.	10,000	32	57.7	V.	I.P. Morris W.S.M.	9,000	..	..	11,000	G.E.	9,000	3	Δ	Y	D.	72.000	G.E.	66,000 33,000 13,200	95,000	Δ	Δ
16	Lehigh Navigation Electric Co.	110,000	25	30,000	100,000	1914	S.	..	..	1500	H.	G.E.	12,500	11,250	.90	11,000	G.E.	3,350	1	Δ	Y	R.	30,150	G.E.	22,000	110,000	Δ	Δ
17	Cedar Rapids Mfg. & Power Co.	110,000	60	90,000	135,000	1914	H.	10,800	30	55.4	V.	I.P. Morris W.S.M.	10,000	7,500	.75	6,600	G.E.	4,000 8,000	1	Δ	Δ	No	72,000	..	6,600	110,000	Δ	Δ
18	Mexican Northern Power Co.	110,000	60	26,000	..	1914	H.	10,000	230	360	H.	Esch. W.	7,800	7,630	.85	4,000	G.E.	2,500	1	Δ	Y	R.	22,500	G.E.	13,200	110,000	Δ	Y
19	Ebro Irrigation & Power Co., Ltd.	110,000	50	50,000	200,000	1914	H.	14,500	164	250	V.	Esch. W.	16,666	10,000	.60	6,600	G.E.	4,444	1	Δ	Δ	No	66,666	W.	25,000 6,000	100,000	Y	Δ
20	Chile Exploration Co.	110,000	50	40,000	160,000	1915	S.	..	..	1500	H.	Esch. W.	10,000	10,000	1.	5,000	S.-S.	10,000	3	Y	Y	No	40,000	S.-S.	5,000	Ca. 100,000	Y	Y
21	Sierra Elec. Power Co.	110,000	..	..	22,500	..	H.	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..

22	Sierra & San Francisco Power Co.	104,000	60	34,000	..	1910	H.	11,750	1500	400	H.	Pelton	8,500	8,500	1.	4,000	G.E.	2,233	1	Δ	Y	D.	26,800	G.E.	11,000	104,000	Δ	Y
23	Great Falls Power Co.	102,000	60	21,000	125,000	1910	H.	6,000	105	225	H.	S.M. Smith	3,500	3,500	1.	6,600	G.E.	1,200	1	Δ	Δ	No	21,600	G.E.	2,500	91,800	Δ	Δ
24	Yadkin River Power Co.	100,000	60	24,000	..	1912	H.	5,900 5,200	45	164	H.	S.M. Smith	6,000 4,500	4,500 3,500	.75 .75	4,000	G.E.	6,250	3	Δ	Y	D.	37,500	G.E.	60,000	100,000	Δ	Δ
25	Colorado Power Co	100,000	60	10,000	10,000	1909	H.	9,000	170	400	H.	I.P. Morris	5,000	5,000	1.	4,000	G.E.	3,333	1	Δ	Δ	No	15,000	G.E.	6,600	90,000	Δ	Δ
26	Great Western Power Co.	100,000	60	50,000	100,000	1909	H.	18,500 18,000	450 525	400	V.	I.P. Morris	12,500 10,000	10,000 10,000	.80 1.	11,500 11,000	G.E.	10,000	3	Δ	Δ	No	50,000	G.E.	11,000	90,000	Δ	Δ
27	Southern Power Co	100,000	60	75,000	..	1909	H.	5,200	69	225	H.	Holyoke Mach. Al.Ch.	3,000	2,550	.85	2,400	W.	4,000	1	Δ	Y	R.	24,000	W.	44,000 13,000 2,400	100,000	Δ	Δ
28	Shawinigan Water & Power Co.	100,000	60	45,000	80,000	1911	H.	18,500	145	225	H.	I.P. Morris	15,000	12,500	.86	6,600	W.	14,000	3	Δ	Y	R.	28,000	G.E.	12,800	85,000	Δ	Δ
29	Los Angeles Aqueduct	100,000	50	22,500	138,000	1914	H.	14,000	870	200	H.	Doble	9,375	7,500	.80	6,600	W.	3,150	1	Δ	Y	D.	28,350	W.	33,000 16,500	..	Δ	Y
30	Tata Hydroelectric Co.	100,000	50	40,000	64,000	1914	H.	11,000	1661 to 1727	300	H.	Esch. W.	10,000	8,000	.80	5,000	S.-S.	3,333	1	Δ	Δ	No	40,000	G.E.	6,600	85,800	Δ	Δ
31	Pfalzwerke, A. G.	100,000	50	10,000	50,000	1915	S.	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
32	Societa Italiana di Elettrochimica	88,000	42	23,280	29,100	1912	H.	8,200	249	420	H.	Riva	7,300	5,820	.80	6,600	Brown Boveri	3,600	1	Δ	Y	No	32,400	Br. Bov.	9,600	72,000	Δ	Y
33	Appalachian Power Co.	88,000	60	20,610	75,000	1912	H.	6,000 3,500	51 37	116 97	V.	I.P. Morris	4,000 2,300	3,600 2,070	.90	13,200	G.E.	6,000	3	Δ	Δ	No	24,000	G.E.	13,200	88,000	Δ	Δ
34	Rio Janeiro Tramway, Light & Power Co.	88,000	50	48,800	90,000	1913	H.	19,000 8,700	1017	300	V.	Esch. W.	12,500 6,000	10,000 4,800	.80	6,300	W.	4,167 1,700	1	Δ	Δ	No	55,600	W.	6,000	80,000	Δ	Δ
35	Sao Paulo Electric Co.	88,000	60	30,000	50,000	1914	H.	14,500	600	600	H.	Voith	12,500	10,000	.80	6,300	W.	3,333	1	Δ	Δ	No	30,000	W.	25,000	80,000	Y	Δ
36	Tasmania Hydro-electric & Metal Co.	88,000	50	..	50,000	..	H.	..	..	..	..	..	1,350	1,700	..	..	W.	..	1	Δ	Y	D.	13,500	W.	6,600	88,000	Δ	Y
37	Mexican Light & Power Co.	85,000	50	58,500	100,000	1910	H.	7,000 13,000 to 14,000	1200 to 1300	300	V.	Esch. W.	7,500 12,500	6,000 11,250	.80 .90	4,000	S.-S. G.E.	2,000 6,000	1	Δ	Y	D.	70,000	G.E.	3,000 210	81,000	Δ	Y

TABLE 79.—DETAILS OF TRANSMISSION SYSTEMS OF THE WORLD OPERATING AT AND ABOVE 70,000 VOLTS—(*Continued*)

No.	Name	Operating Voltage	Frequency Cycles	Rating of Plant, Kw		Beginning of Operation	Turbines						Generators					Step-up Transformer							Step-down Transformers			
																				Conn.					Line Voltage		Conn.	
				Present	Ultimate		Hydr. of Steam	H.P.	Head Ft.	R.P.M.	Shaft. Hor. or Vert.	Manufacturer	Kva.	Kw.	P.F.	Voltage	Manufacturer	Kva.	Phases	L. T.	H. T.	Y. Gr. Dir. or with Res	Total Kva. Connected to Transmisson Lines	Manufacture	L.T.	H.T.	L. T.	H. T.
38	Toronto Power Co.	85,000	25	80,000	95,000	1914	H.	13,000 to 15,000	133 to 135	250	V.	Esch.W. I.P. Morris	7,500 10,000	6,000 8,000	.80	12,000	G.E.	2,666 6,000	1 3	△	△ Y	No	51,000	G.E.	12,000	80,000	△	△
39	Victoria Falls & Transvaal Power Co.	84,000	50	40,667	40,667	1913	S.	..	..	1000	H.	A.E.G.	12,500 18,000	8,333 12,000	.67	5,000	A. E.G.	12,500 9,000	3	△	Y	R.	61,000	S.-S. A.E.G. W.	20,000	Ca. 80,000	Y	△
40	Northern Power Co	80,000	60	..	..	..	H.	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	W. G.E.	4,400 22,000	..	..	..
41	Energia Electrica de Cataluna	80,000	..	..	Over 100,000	? 1913	H.	..	2620	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	11,000	..	..	..
42	Swedish State Railways	80,000	15	26,400	52,800	1915	H.	12,500	164	225	H.	..	10,500	..	..	4,000	All.Sv. El.Akt.	..	..	..	..	..	..	..	15,000	..	..	..
43	Katsuragawa Denryoku Kabushiki Kaisha	77,000	50	22,400	56,000	1912	H.	8,000	470	500	H.	Voith	7,000	5,600	.80	11,000	G.E.	3,500	1	△	Y	R.	31,500	G.E.	11,000	70,000	△	Y
44	Southern California Edison Co.	75,000	50	20,000	..	1907	H.	2x5375	874	250	H.	Al. Ch.	5,000	5,000	1.	2,300	G.E.	1,667	1	△	Y	D.	20,000	G.E.	30,000 15,000 2,300	..	Y Y △	Y
45	Au Sable Electric Co.	72,000	30	3,000	3,000	1906	H.	7,000	38	225	H.	Leffel	1,500	1,500	1.	6,600 (6,000)?	W.	1,200	1	△	△	No	3,600	W.	6,600	66,000	? △	? △
46	City of Milan	72,000	42	21,000	..	1910	H.	12,000	1040	315	H.	Riva	8,750	7,000	.80	10,000	Br. Bov.	2,850	1	△	Y	R.	25,650	Br. Bov.	8,650	65,000	△	Y
47	Societa Generale Elettrica dell' Adamello	72,000	42	Ca. 45,000	Ca. 75,000	1910	H.	6,500 5,000	2985 1542	420	H.	Esch.W. Riva	7,333 5,000	5,500 4,000	.75 .80	13,000 12,000	Br.-Bov A.E.G.	2,700	1	△	△	No	40,500	G.E.	13,000	60,000	Y	Y
48	Montana Co.	70,000	60	21,500	60,000	1901	H.	1,000 4,000	40 65	157 225	H.	Day-Sm. S.M.Sm.	750 2,800	750 2,800	1.	550 2,400	W.	1,250 2,000	1	△	△	No	25,000	W.	2,400	60,000	△	△

49	Hidroelectrica Espanola Molinar	70,000	50	27,000	27,000	1910	H.	7,200	217	428	H.	Voith	6,750	5,400	.80	7,000	S.-S.	6,750	3	Y	Y	No	27,000	S.-S.	6,000	60,000	Y	Y
50	Pennsylvania Water & Power Co.	70,000	25	71,500	Over 100,000	1910	H.	13,500 to 17,000	53 to 63	94 116	V.	I.P. Morris	7,500 10,000 12,000	7,500 10,000 12,000	1.	11,000	G.E. W.	7,500 10,000	3	△	Y	R.	71,500	G.E. W.	13,000	60,000	Y	△
51	Guadalajara, Mexico	70,000	50	Ca. 8,000	8,000	Ca. 1911	H.	4.000	215	375	H.	Esch.W.	3,500	3,500	1.08	10,000	S.-S.	4,000	3	Y	Y	No	12,000	S.-S.	20,000 3,000	67,500	Y	Y
52	Societa Elettrica Riviera di Ponente	70,000	50 16⅔	27,000	60,000	1911	H.	10,000	230	500	H.	Riva	..	7,500	..	6,000	A.E.G. S.-S.	4,690 3,100	3 1	Y	Y	R.	60,000	A.E.G	12,000	..	Y	Y
53	Swedish State Railways	70,000	25	17,600	52,800	1915	H.	14,000	164	250	H.	..	11,000	8,800	.80	10,000	All.Sv. El.Akt.	3,670	1	△	Y	D.	11,000	..	..	..	..	..
54	City of Winnipeg	66,000 to 72,000	60	15,000	48,000	1911	H.	5,200	45	164	H.	Boving	3,750	3,000	.80	6,600	Vickers	3,000	1	△	△	..	18,000	W.	12,000	60,000	△	△

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